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# Analysis of Acoustic Modeling and Sound Propagation in Aircraft Noise Prediction

*Kenneth J. Plotkin*  
*Wyle Laboratories, Arlington, Virginia*

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September 2006

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## 1.0 Introduction

In May and June 1997, a noise model validation project was conducted at Denver International Airport.<sup>1</sup> Over a period of six weeks, noise data were collected at 31 fixed sites (the airport's permanent noise monitors) and additional monitors temporarily deployed at up to 19 sites for the study. Figure 1 shows the airport and noise monitor sites. Sites marked with closed circles are the permanent noise monitors, and those marked with open circles are the temporary monitors.

Recorded noise data consisted of time histories of A-weighted levels at one second intervals. Radar tracking data was archived at the same time. United Airlines and Delta Airlines supported the study by providing the actual equipment (airframe and engine types) and weights for all operations during the measurement period. United and Delta also provided flight manual data from which takeoff and climb power could be estimated, and power information for a sample of flights.

A total of 703 flights were analyzed, with about 3000 sound exposure level (SEL) values computed from the FAA's Integrated Noise Model (INM)<sup>2</sup> compared to measured SEL. INM was run in point-to-point mode, with altitude profiles and flight tracks taken directly from radar. Power profiles were based on the data supplied by the airlines. Actual temperature and humidity were used when calculating power. The acoustic part of the calculations was performed using the supplied NPD database and standard INM algorithms.

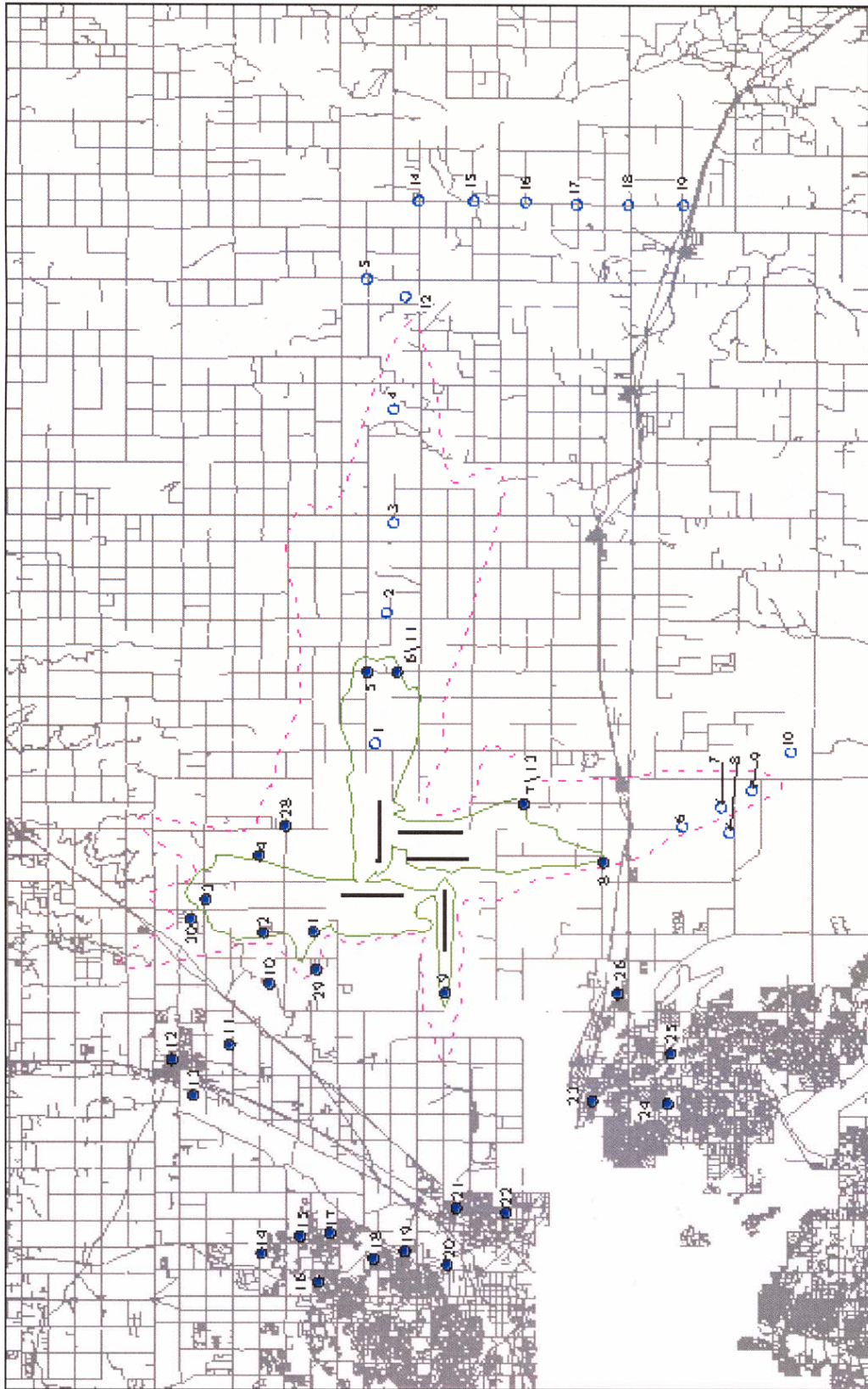
Figure 2 shows a sample result from the 1997 study, a regression between measured and predicted SEL, with 2437 data points compared. The regression fit is shown as a solid line, and a 1:1 perfect fit is indicated by a dashed line. There is substantial spread, and on average INM predictions are about 5 dB lower than measured values at high SEL and about 10 dB lower at low SEL. This pattern was typical for most regression analyses.

The current study is an analysis of a small sample of the 1997 data, focusing on acoustic modeling and sound propagation issues. Ninety departures from Runway 8 were selected. These flights had the following characteristics:

- Operations which had been analyzed in Reference 1. Power profiles and INM calculations of SEL were available for these
- Straight (or nearly straight) flight tracks
- Good noise data on as many monitors as possible

Thirty of the selected flights generated good noise data on four or more monitors. Part of the current analysis was based on examining whether differences between measured and predicted levels were consistent, e.g., if the prediction was low at one site would it be consistently low at the other sites. An objective of this study was to see whether the differences in Reference 1 were associated with noise source data, propagation, or flight modeling. Propagation analysis concentrated on atmospheric absorption of sound and





Scale



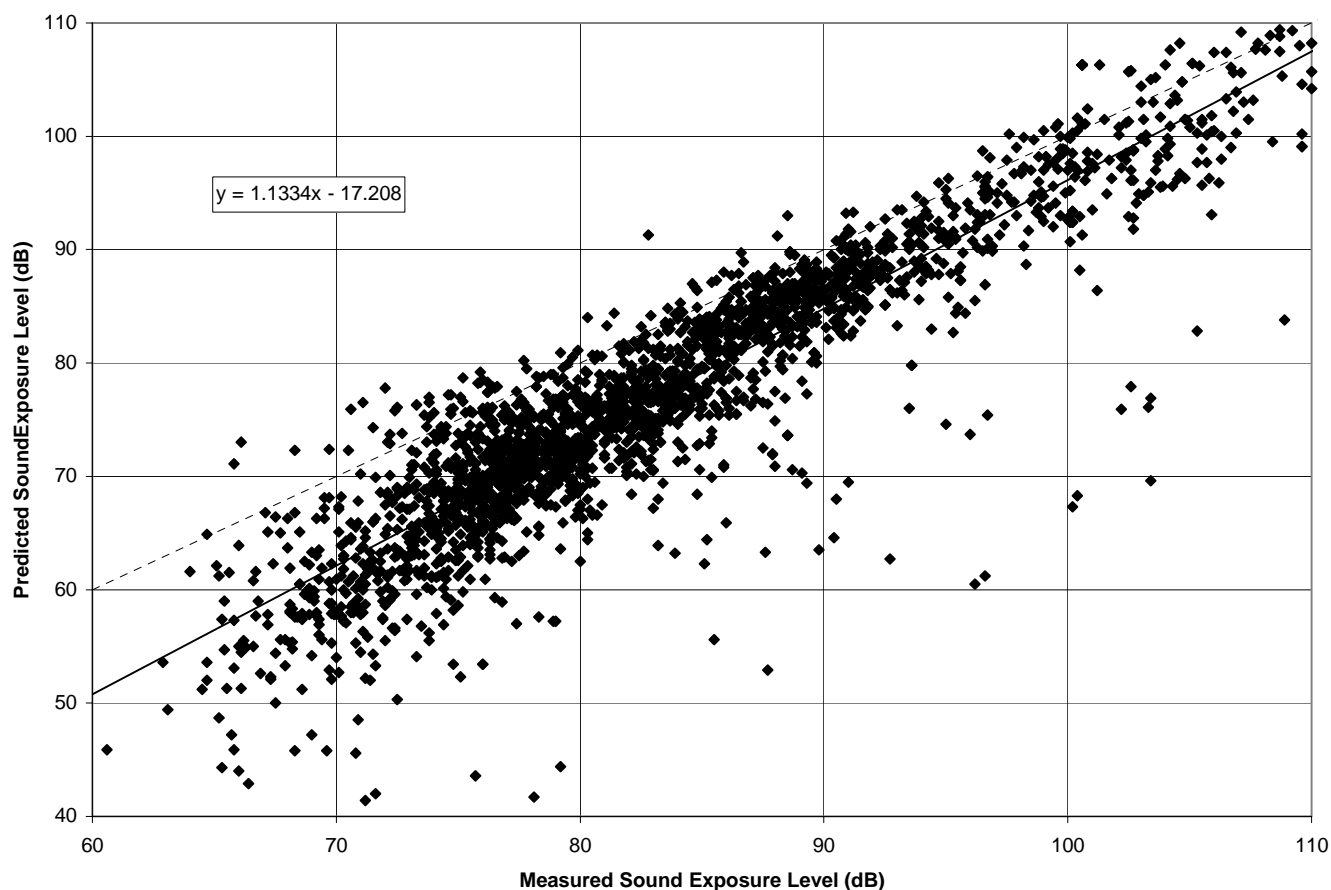
Legend

- 65 Ldn Contour
- - - 55 Ldn Contour
- Runway
- Existing Noise Monitor
- Supplementary Monitor

Figure 1

Runway and Measurement  
Site Layout at Denver  
International Airport (DIA)

Source: TDEC/LRM 1/2018



**Figure 2. Comparison Between Measured and INM 5.1a Calculated SEL, 2437 Data Points**

ground effects. Selection of straight tracks minimized issues related to segmentation and noise fraction in the INM calculation.

INM is an integrated model, in that its acoustical basis consists of line sources representing the time-integrated noise from a complete flyover. Noise data in INM (the NPD curves) are generally supplied by the aircraft manufacturers, and are fixed to standard temperature and humidity. In order to modify propagation to actual conditions, noise calculations in this study were performed using the aircraft noise simulation model NMSIM,<sup>3</sup> which calculates the noise level as a function of time. As a simulation model, its acoustical basis consists of point sources which move dynamically in time. It accounts for geometric spreading, air absorption and ground effect. Both models represent the same physical phenomena, but do so with different levels of detail and some different choices in particular algorithms.

NMSIM requires a directional, spectral definition of the aircraft noise source at a reference distance of 1000 feet. This was prepared in two different ways. First, it was estimated from INM NPD curves and spectral classes. This provided source functions for all power settings, but with uniform spectral directivity characteristics. Second, directional patterns were extracted from end-of-runway measurements reported in Reference 4. This provided actual spectral directivity, but at only one power setting.

---

Section 2 of this report presents comparisons between measured and predicted noise for the ideal subset of flights examined in this study. Effects of temperature and humidity are analyzed in Section 3.

---

## 2.0 Comparison of Measured SEL with INM and NMSIM Predictions

### 2.1 Selected Flights

Ninety flights, of the 703 available, were selected for analysis. These were all nominally straight-out departures from Runway 08. There were 264 noise measurement points for these 90 flights. Most of these (72) were 737s. There were twelve 727s and six 757s in the selection.

Figure 3 shows a comparison between measured SEL and that predicted by INM 5.1a. This is a subset of the data shown in Figure 2, and has similar characteristics. Points marked "2", "3" and "5" correspond to 727, 737 and 757, respectively, aircraft. INM calculations were done in point-to-point mode, where the flight path, air speed and power (net corrected installed thrust) were specified at a sequence of points. The flight path was taken directly from radar data. Power was calculated from methods described in Reference 1. Those methods replicate the process used by the airlines to calculate power schedule for each flight.

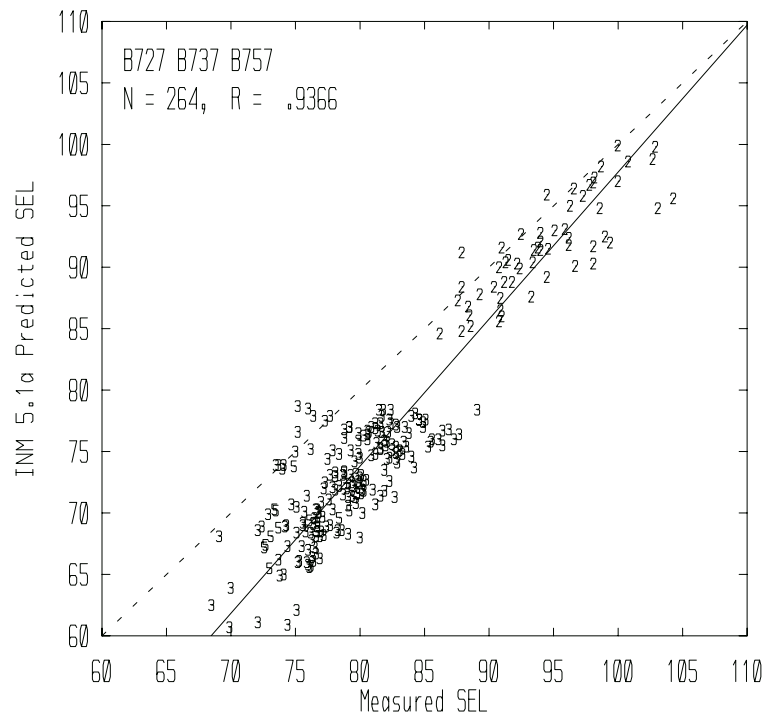
In the time since the analysis of Reference 1 was performed, INM has been updated. The updates involved improvements to the user interface and adjustment to the profile calculations. Because point-to-point mode was used, INM's profile calculations were bypassed, so (in principal) the current version of INM should yield the same results as from INM 5.1a.

Figure 4 shows a comparison between measured SEL and that predicted by INM 6.0b. The same flight profiles were used in this analysis as before. Note that the agreement between measured and predicted is better than seen in Figure 3. It is not known why this occurs: there were no significant changes to the noise propagation algorithms from INM version 5 to version 6. Figure 5 shows a comparison between INM 5.1a and INM 6.0b predictions for these 264 data points.

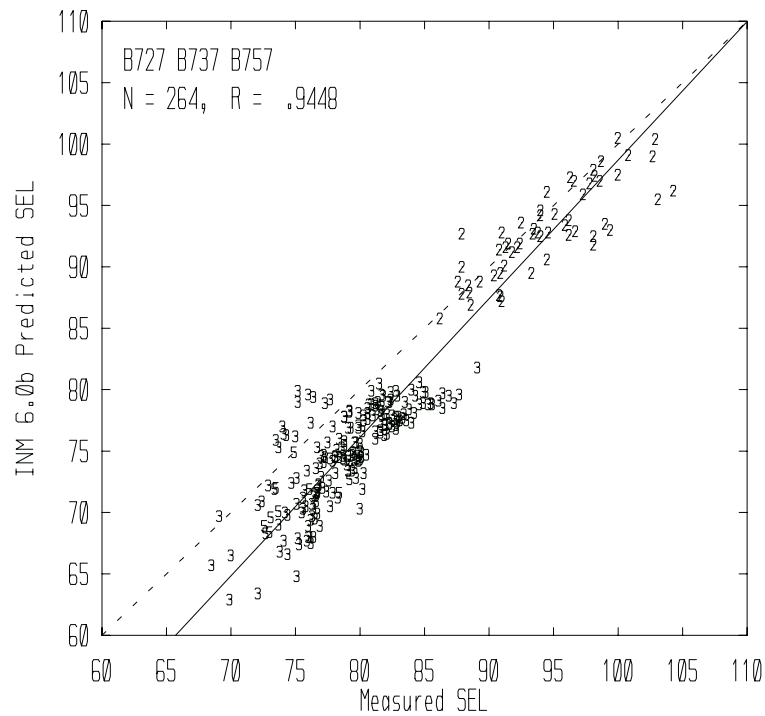
### 2.2 NMSIM Calculations: Baseline

NMSIM<sup>3</sup> is a three dimensional spectral model, and requires a 3-D spectral source. This source was extracted from the INM NPD curves, for each aircraft type, by the following process:

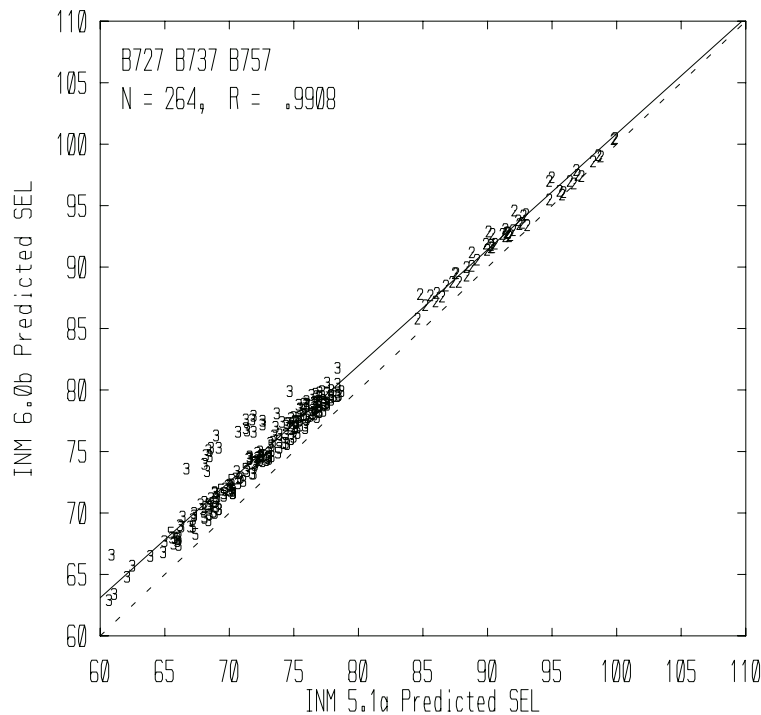
1. A nominal A-weighted level as a function of thrust was taken at 1000 feet by subtracting 10 dB from SEL in the NPD curves.
2. Spectra were taken from the INM spectral classes. The spectrum was taken to be the departure spectrum at the highest power setting, the approach spectrum at the lowest power, and interpolated between the two at intermediate powers.
3. Directivity in the fore-aft direction was based on INM's start of takeoff roll directivity adjustment. Lateral directivity (roll direction) was assumed to be axisymmetric.



**Figure 3. Comparison Between Measured and INM 5.1a Calculated SEL, 264 Data Points from Current Flight Subset**



**Figure 4. Comparison Between Measured and INM 6.0b Calculated SEL, 264 Data Points from Current Flight Subset**



**Figure 5. Comparison Between Measured and INM 6.0b Calculated SEL, 264 Data Points from Current Flight Subset**

4. NMSIM was run for a straight level flyover at 1000 feet, 160 knots, at each power setting tabulated in NPD.
5. Calculated SELs in Step 4 were compared to NPD SEL. The 10 dB offset (Step 1) was replaced with a calibrated offset such that NMSIM SEL matched NPD SEL.

The offset adjustment described in Step 5 was a single value applied at all power settings; it was not tuned to individual points in NPD.

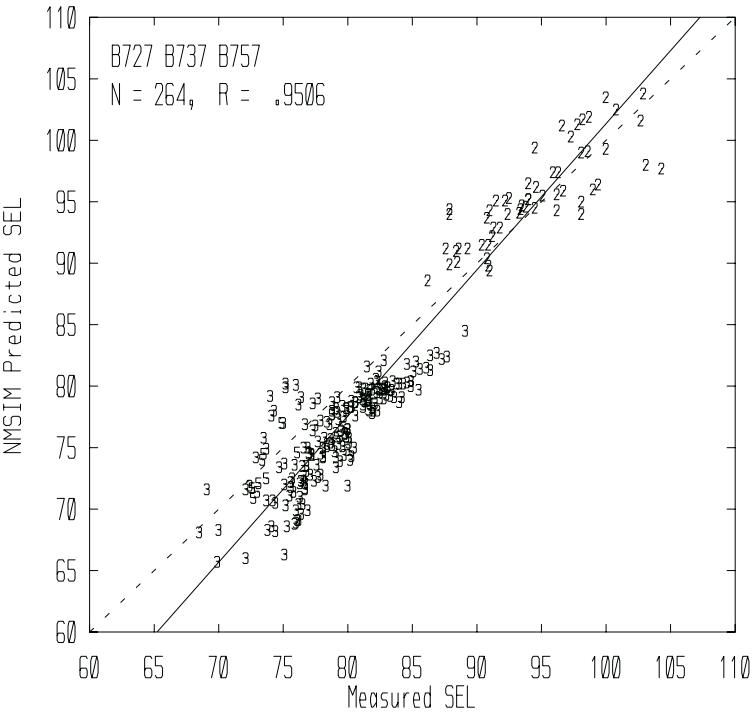
Table 1 shows, for a 737, SEL from the original NPD curves and SEL as computed from NMSIM for steady flight at 160 knots and various distances. The calculations were performed at standard temperature and humidity. While agreement is not perfect, it is fairly close. Some differences are to be expected, if only because of the differences in air absorption in the two models. (NMSIM uses ANSI/ISO standard absorption, while INM uses that defined in SAE 1845.) Agreement is generally within a few tenths of a dB at higher thrust values (above 10,000 pounds) that were present for the departures analyzed here. There are larger differences at lower power settings. If NMSIM were to be used for approaches, a more refined source model would be required.

Figure 6 shows a comparison between SEL calculated from NMSIM and measured SEL, in a format similar to Figures 3 and 4. Just as INM 6 predictions were better than INM 5, NMSIM predictions are better than INM 6. It is not clear why these should be different, particularly since (as shown in Table 1) NMSIM calculations for NPD conditions match NPD values. The differences in the real-flight calculations are much greater than any errors introduced in developing the NMSIM source levels. Analysis of the details of the code in either model is

well beyond the scope of the current project. The results from both versions of INM and from NMSIM are, however, generally parallel, so trends from NMSIM are expected to apply in general to any similar physically based model. NMSIM was used for this study because of the flexibility inherent in its moving point source, time history formulation.

**Table 1. 737 NPD SEL and NMSIM Emulation**

<b>a. NPD data, 630 feet to 6300 feet</b>									
NOISE	N	THR_SET	C	L_630	L_1k	L_2k	L_4k	L6.3k	
CFM563	S	3690.00	N	88.5	85.0	79.6	73.0	67.9	
CFM563	S	6180.00	N	90.6	87.3	82.0	75.7	70.8	
CFM563	S	9880.00	N	90.7	87.6	82.7	76.8	72.1	
CFM563	S	13190.00	N	93.1	90.2	85.4	79.6	75.0	
CFM563	S	17273.00	N	96.5	93.7	89.1	83.4	78.9	
CFM563	S	21180.00	N	100.9	98.4	94.0	88.5	84.1	
<b>b. NMSIM calculations</b>									
				<i>Distance</i>					
	Thrust			630	1000	2000	4000	6300	
	3690.			86.6	84.9	80.2	74.4	69.8	
	6180.			88.9	87.3	82.6	76.7	72.2	
	9880.			89.2	87.6	82.9	77.1	72.5	
	13190.			91.8	90.2	85.6	79.8	75.2	
	17273.			95.3	93.8	89.1	83.4	78.8	
	21180.			100.1	98.5	93.9	88.2	83.7	



**Figure 6. Comparison Between Measured and NMSIM Calculated SEL, 264 Data Points**

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## 2.3 Consistency within Flights

A question not addressed in the statistical analysis of Reference 1 was within-flight consistency, that is, were measurements at several points from a given flight consistently higher or lower than predictions, or were differences random. Consistent differences, i.e., always high or always low, would suggest a problem with NPD values or a stable propagation effect such as air absorption. Inconsistent patterns would suggest stochastic effects, such as atmospheric turbulence or unsteady gradients.

Thirty of the selected flights – ten 727 and twenty 737 – yielded measurements at four or more sites. These are shown in Figures 7 (ten 727s) and 8 (twenty 737s). Each plot within these figures shows, as a function of track distance from brake release, measured SEL, INM 5 predictions, and NMSIM predictions. (Jumps in the 727 data at small track distances are associated with two sites at about the same distance but laterally separated.) In general, trends are consistent, suggesting that stochastic propagation effects do not have a substantial effect on SEL. As expected from Figures 3 and 6, both NMSIM and INM tend to underpredict levels, INM more so than NMSIM. INM and NMSIM results in Figures 7 and 8 are generally parallel to each other, with some irregularities seen in the measurements relative to predictions. 727 measurements tend to be around the NMSIM predictions, while 737 measurements are above both predictions. 727 measurements also tend to be slightly more irregular relative to prediction than 737.

There is a qualitative appearance in Figures 7 and 8 of greater underprediction at larger distances. Figures 9 and 10 show the difference between predicted and measured SEL as a function of distance for each of the three models, for 727s and 737s. There is a weak relation with distance for 727s, with a slight rise in prediction (about 2 dB) for both INM versions and a similar decline for 737s.

## 2.4 Propagation Effects

There are two propagation effects which could explain the differences between the distance behaviors of 727s and 737s. One is spectral content, and the other is lateral attenuation.

Figure 11 shows the spectral shapes, at takeoff power, for the two aircraft types. These are from the spectral classes in INM, and represent shape only: they are shifted so as to be 70 dB at 1 kHz. This shift (which is part of the format of the spectral classes) allows comparison of the relative frequency content. Note that the 727 has a greater concentration of energy in the 100 to 500 Hz range, while the 737's spectrum has less low frequency content. Low frequencies are subject to less air absorption than high frequencies, so the behavior seen in Figures 9 and 10 (737 noise decaying more rapidly with distance) is consistent with expectations. Air absorption by molecular relaxation mechanisms is discussed in more detail in Section 3.

The second effect is lateral attenuation. At low incidence angles, sound is attenuated by ground impedance effects. Aircraft can also have a lateral directivity pattern, sometimes referred to as shielding or as installation effect. INM uses a lateral attenuation algorithm defined in SAE AIR 1751<sup>5</sup>, which incorporates both effects. NMSIM uses ground impedance algorithms included in Rasmussen's terrain effects models.<sup>6</sup> The algorithm in SAE 1751 was empirically derived from measurements primarily from 727s. The shielding portion of the 1751 method is considered to be typical of rear-engine aircraft. Ground impedance effects



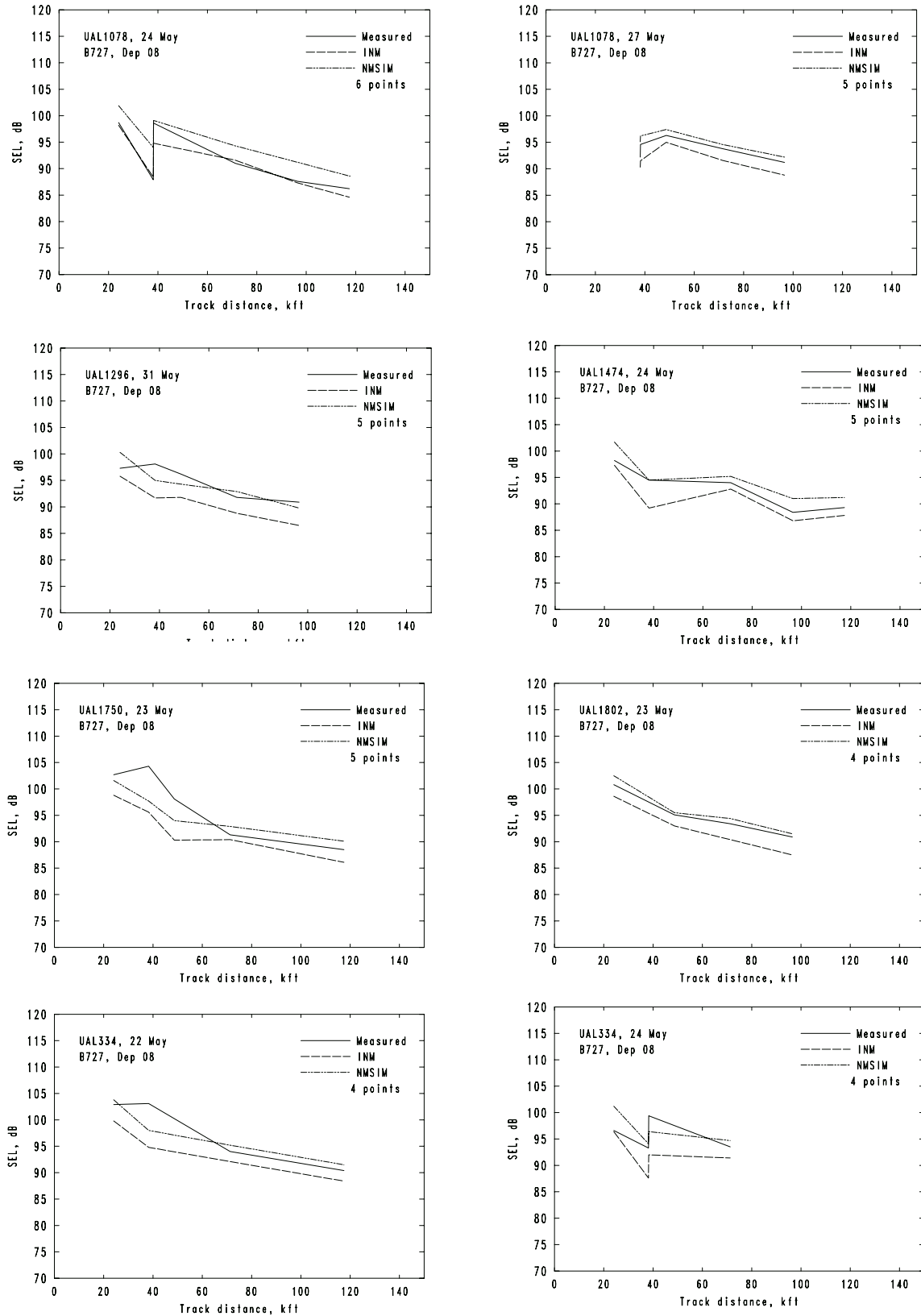
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tend to be negligible at elevation angles above 10 degrees,<sup>4</sup> while the full 1751 method goes up to about 45 degrees.

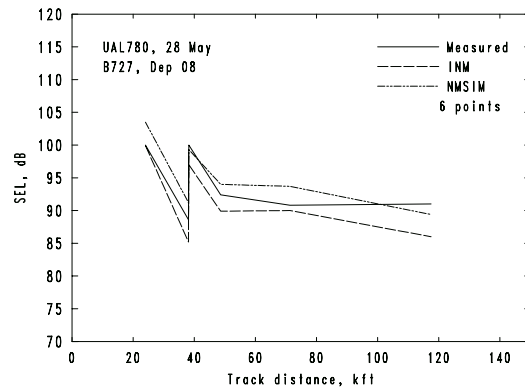
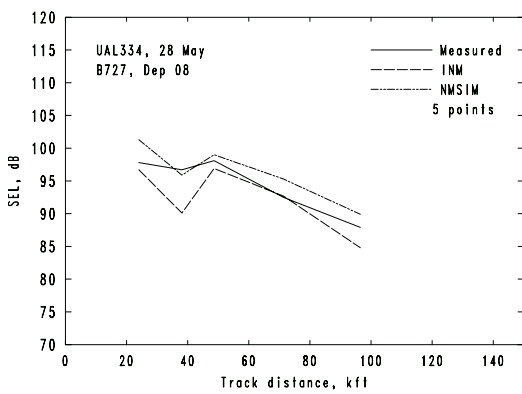
Figures 12 and 13 show the same data set (differences between predicted and measured) as a function of elevation angle. Elevation angles are all above 10 degrees, so any angular dependence is likely to be associated with shielding. While there are some variations within the 727 data, the mean is fairly flat: there is little (up to 2 dB) or no difference with angle. That indicates that the 1751 lateral attenuation algorithm has the generally correct behavior. Also, while slopes are small, there is a noticeable difference between the slope of the INM results and that of the NMSIM results. That is to be expected, since NMSIM accounts for only ground impedance, and not shielding.

The 737 data in Figure 13 has a distinct downward slope with decreasing elevation angle. Aircraft with wing mounted engines, like the 737, are expected to have different shielding than tail mounted engines like the 727. In a recent set of measurements, Fleming<sup>7</sup> showed that 1751 lateral attenuation is successful for tail mounted engines, but tends to underpredict noise for wing mounted engines. That is the trend seen in Figures 12 and 13.

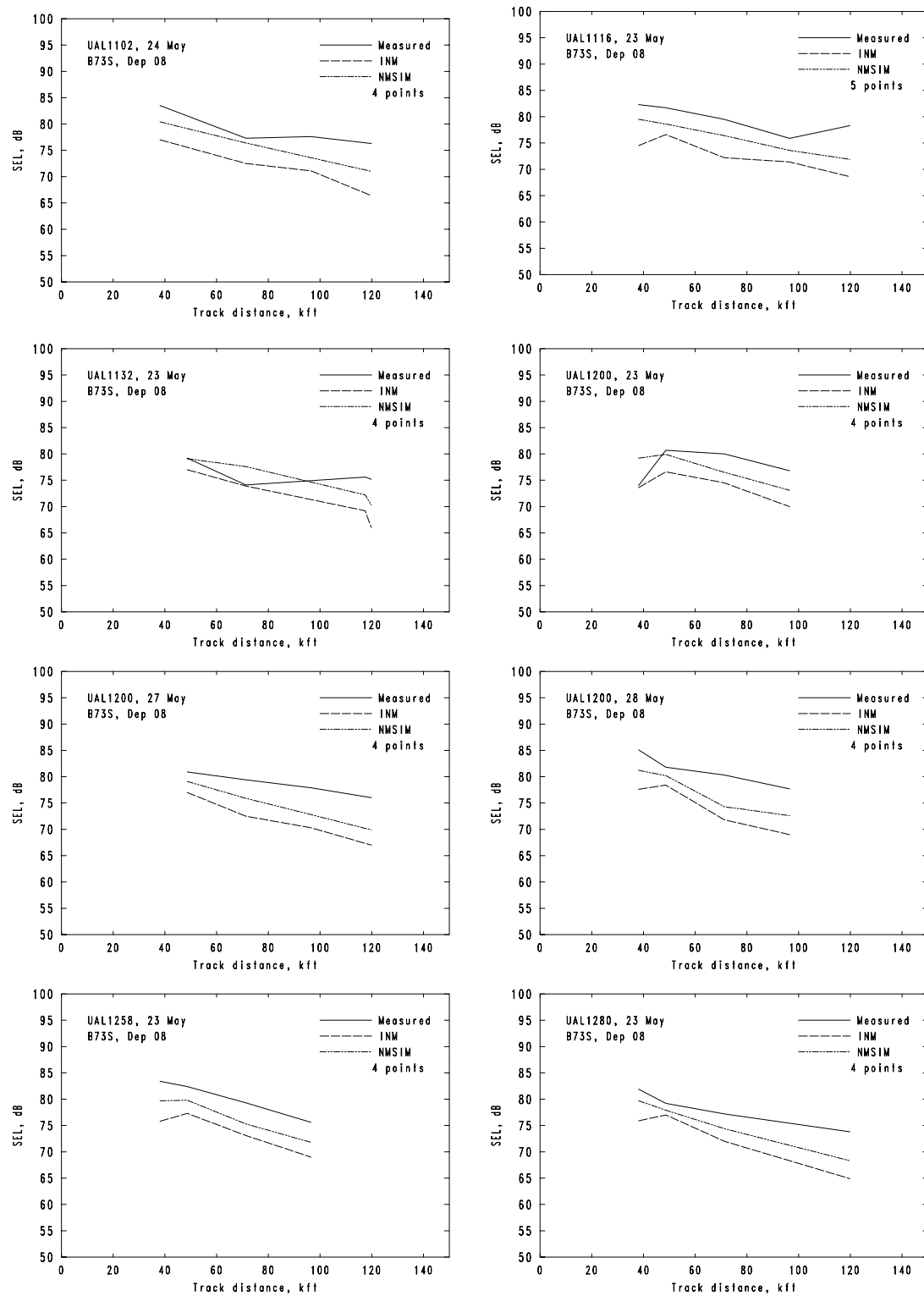
The distance trend seen earlier in Figures 9 and 10 may not be entirely due to spectral effects and absorption. Elevation angles are likely to be lower at small track distances, where altitude is low and a lateral offset can more easily result in a lower angle. Figure 14 shows the correlation between elevation angle and track distance for this data set. Note that the expected dependence is present, and is quite clear at angles below 45 degrees where the SAE AIR 1751 method applies. The role of air absorption is analyzed in more detail in Section 3.



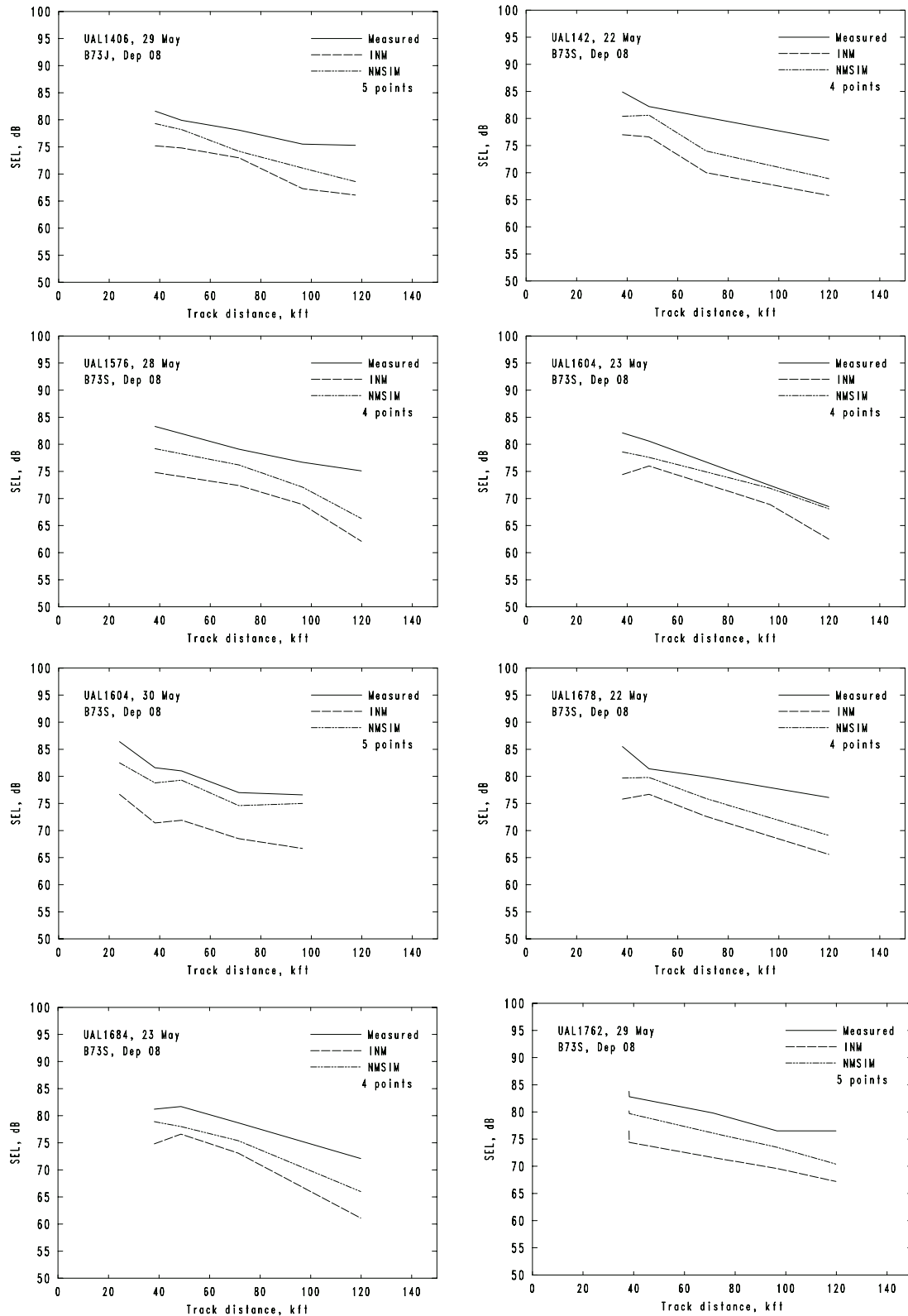
**Figure 7. Measured and Predicted (INM and NMSIM) SEL as a Function of Track Distance for Ten 727 Departures**



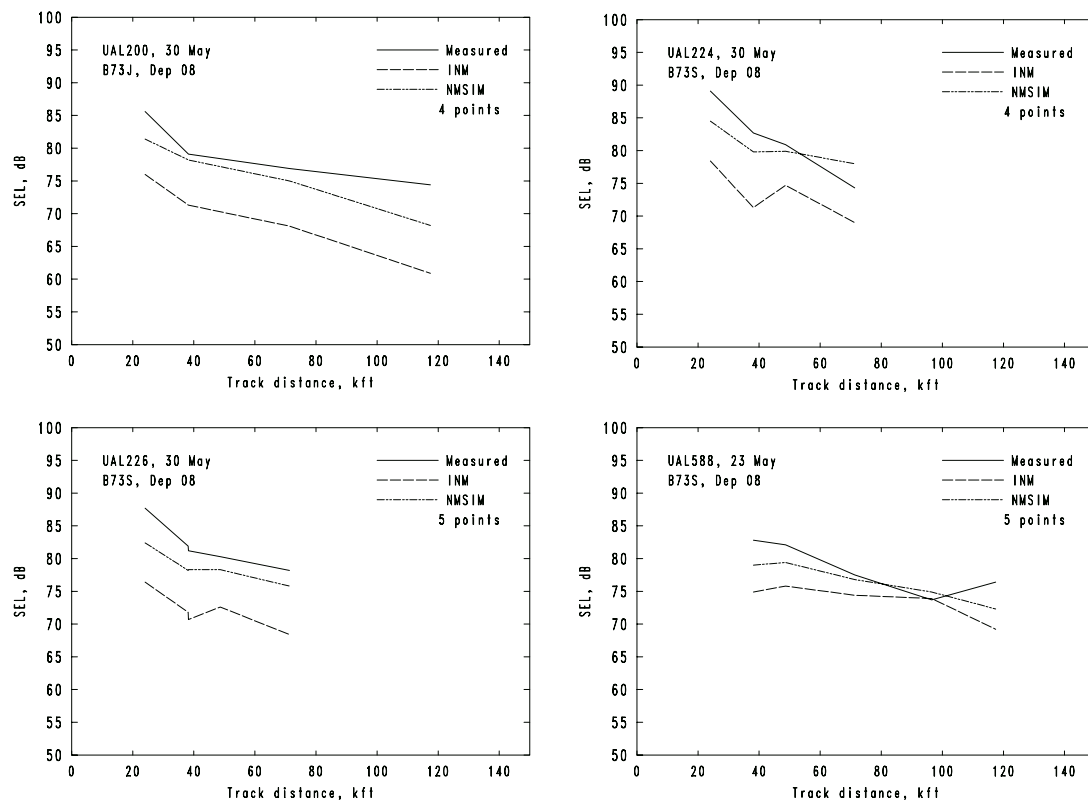
**Figure 7. Measured and Predicted (INM and NMSIM) SEL as a Function of Track Distance for Ten 727 Departures - *concluded***



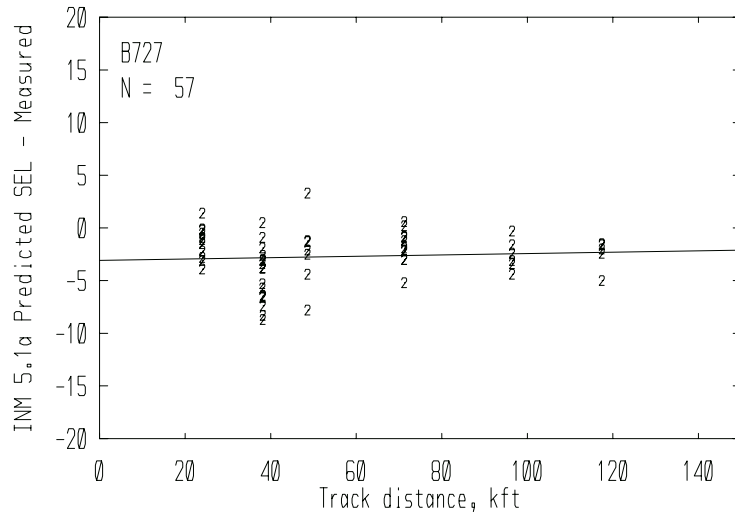
**Figure 8. Measured and Predicted (INM and NMSIM) SEL as a Function of Track Distance for Twenty 737 Departures**



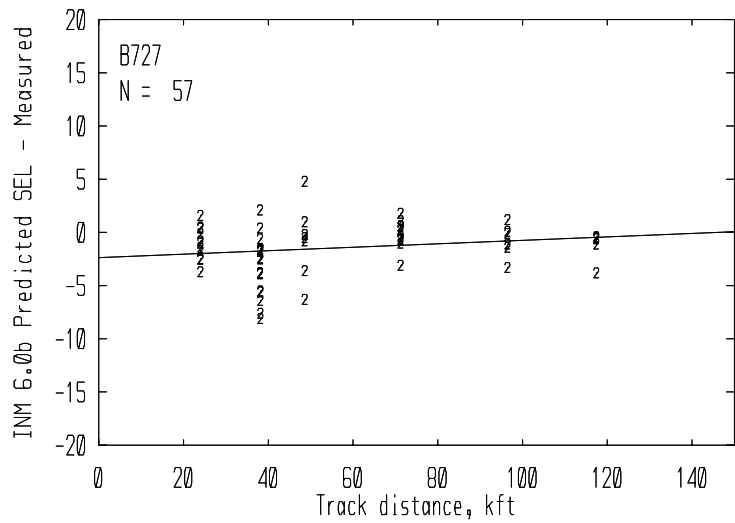
**Figure 8. Measured and Predicted (INM and NMSIM) SEL as a Function of Track Distance for Twenty 737 Departures – *continued***



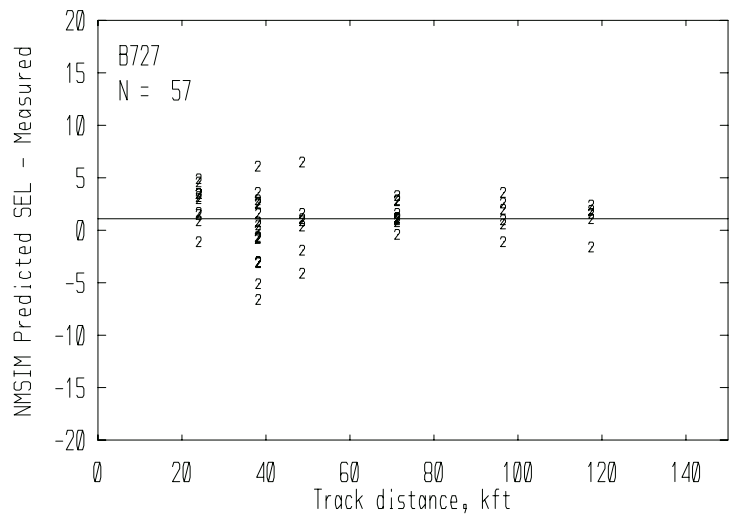
**Figure 8. Measured and Predicted (INM and NMSIM) SEL as a Function of Track Distance for Twenty 737 Departures – *concluded***



**a. INM 5.1a**

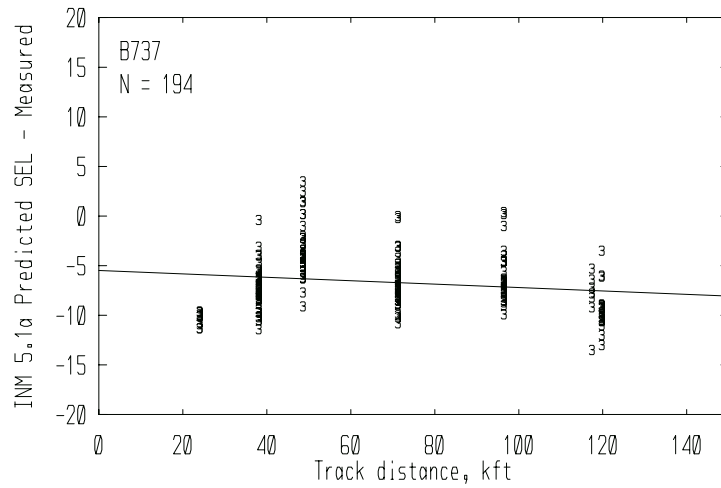


**b. INM 6.0b**

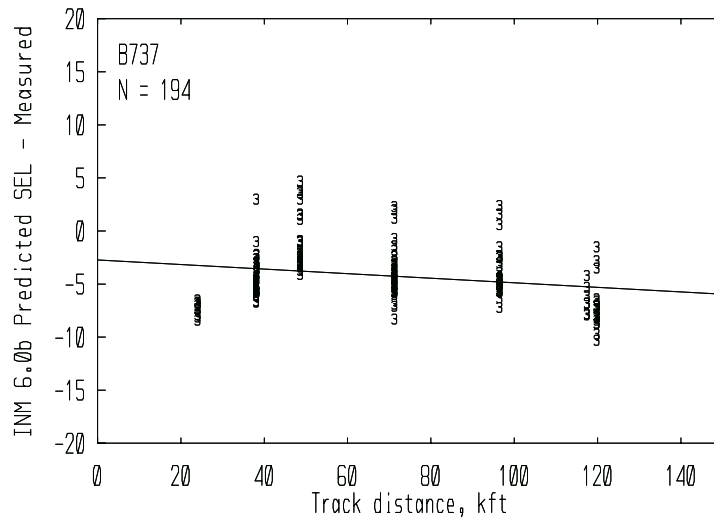


**c. NMSIM**

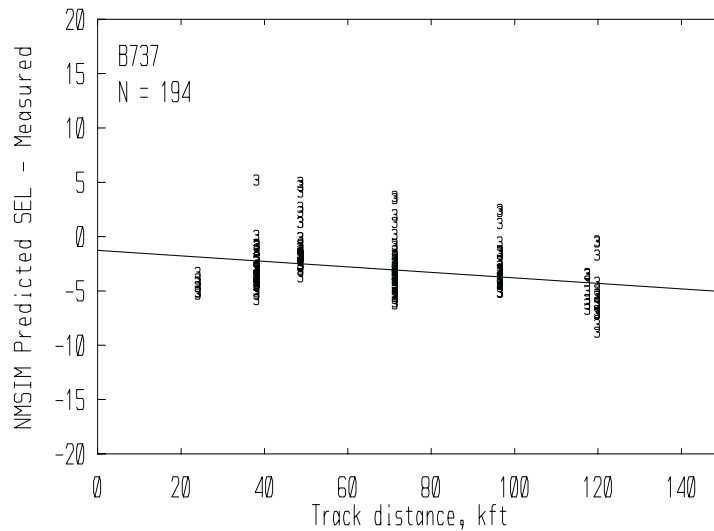
**Figure 9. Differences Between Predicted and Measured SEL with Distance, 727**



**a. INM 5.1a**



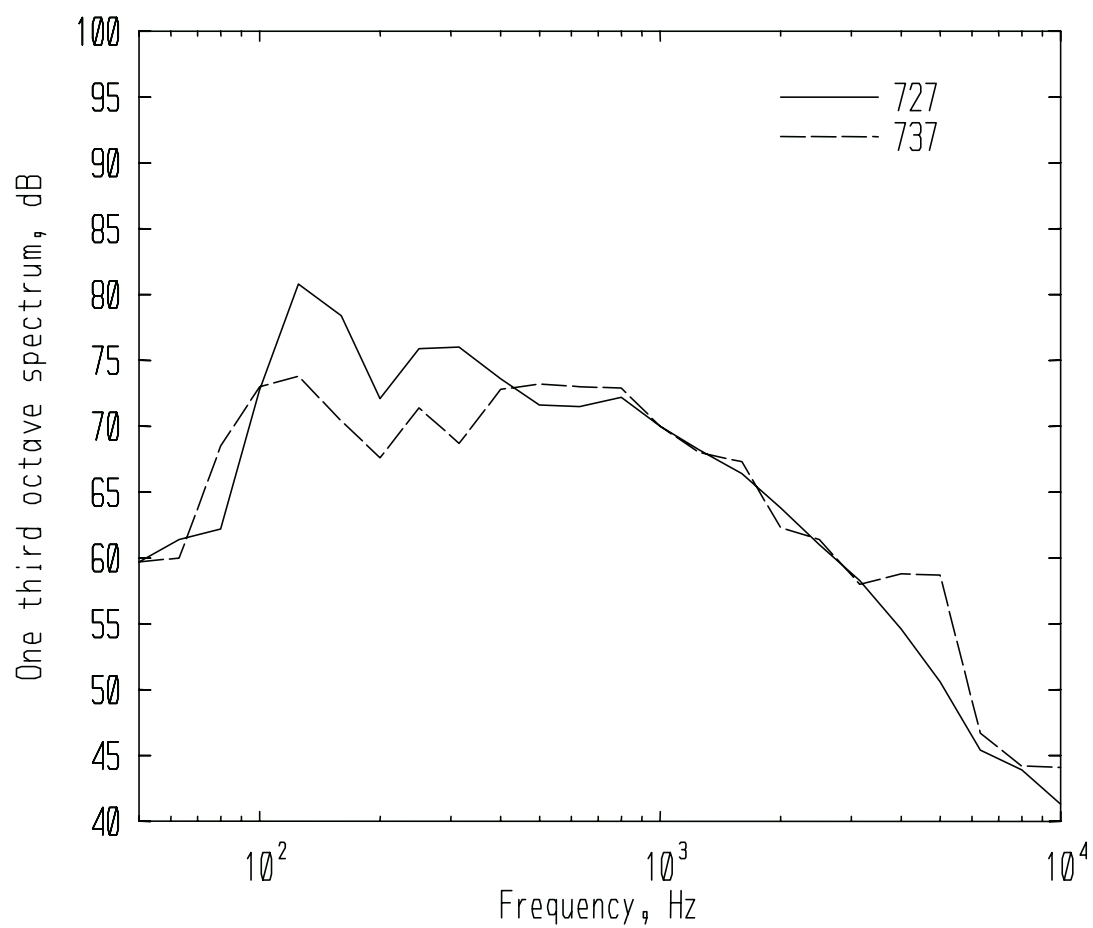
**b. INM 6.0b**



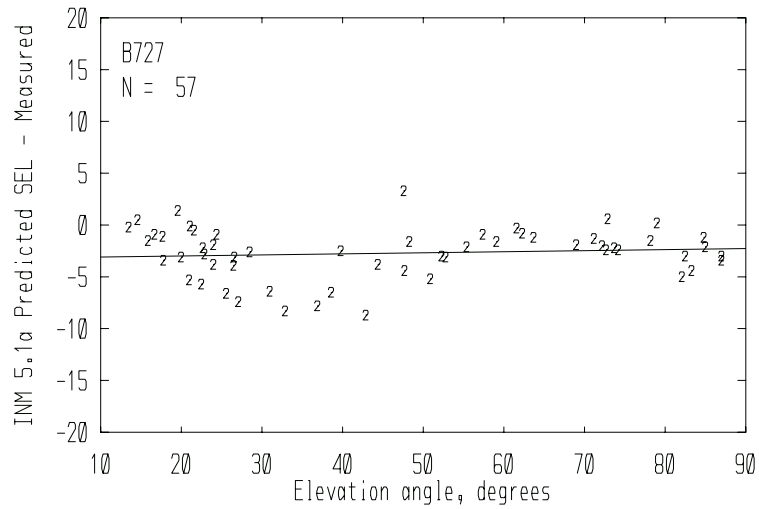
**c. NMSIM**

**Figure 10. Differences Between Predicted and Measured SEL with Distance, 737**

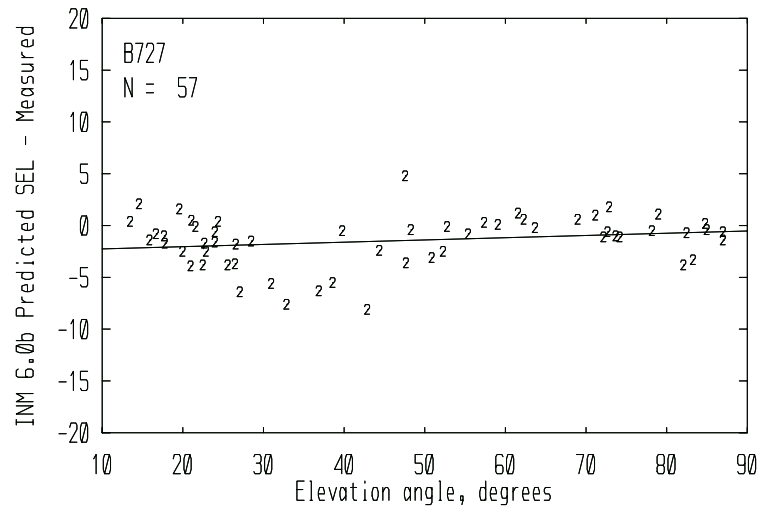




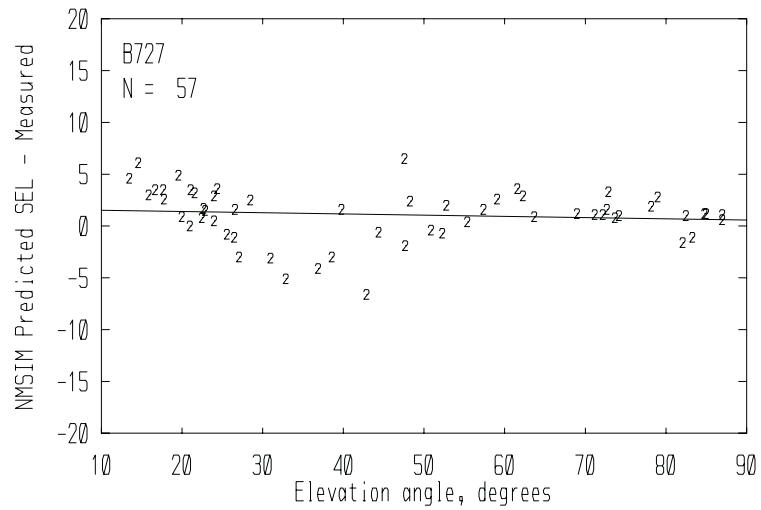
**Figure 11. One Third Octave Band Spectral Shapes for 727 and 737**



**a. INM 5.1a**

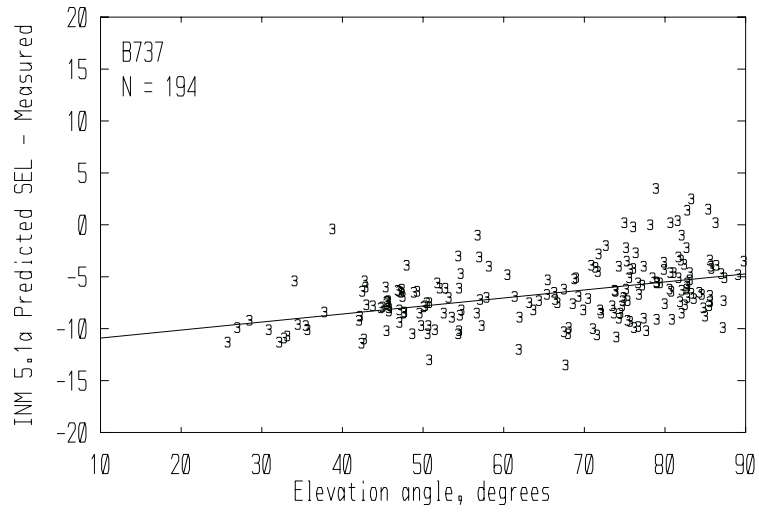


**b. INM 6.0b**

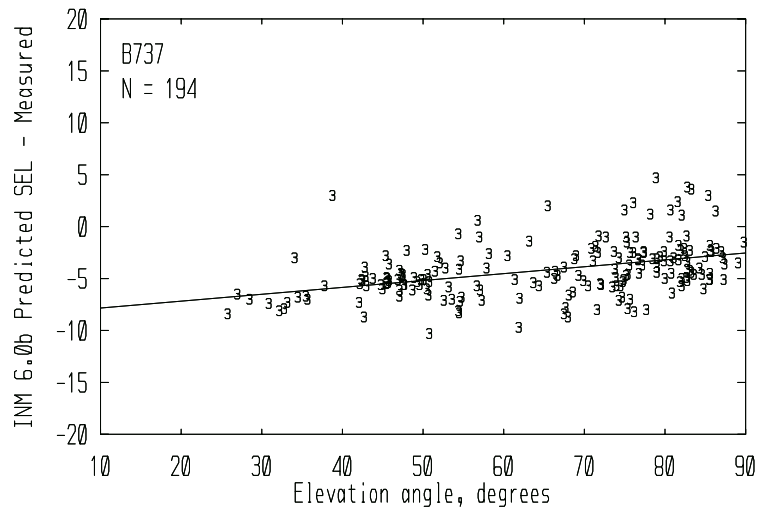


**c. NMSIM**

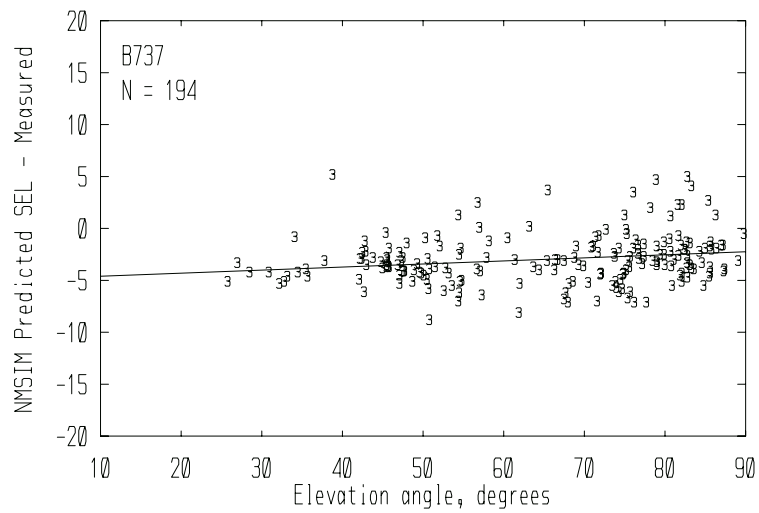
**Figure 12. Differences Between Predicted and Measured SEL with Elevation Angle, 727**



**a. INM 5.1a**

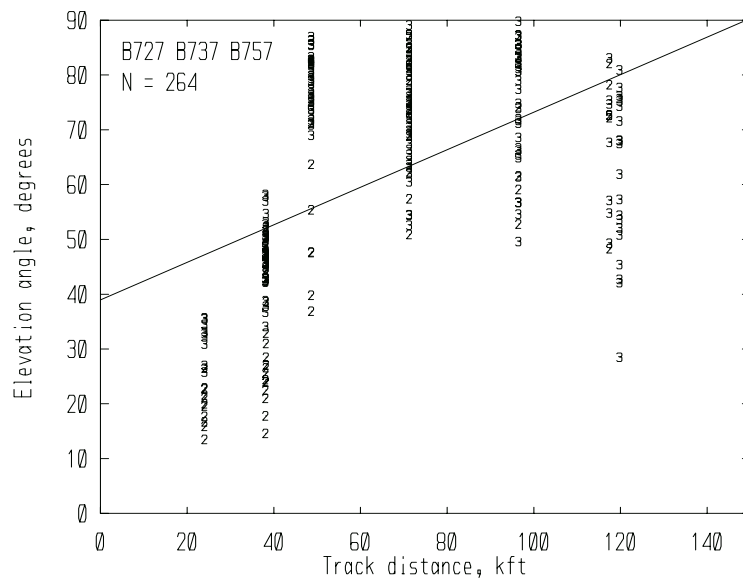


**b. INM 6.0b**



**c. NMSIM**

**Figure 13. Differences Between Predicted and Measured SEL With Elevation Angle, 737**



**Figure 14. Correlation Between Track Distance and Elevation Angle for Current Data Set**

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## 3.0 Atmospheric Absorption

### 3.1 Actual vs Nominal Absorption

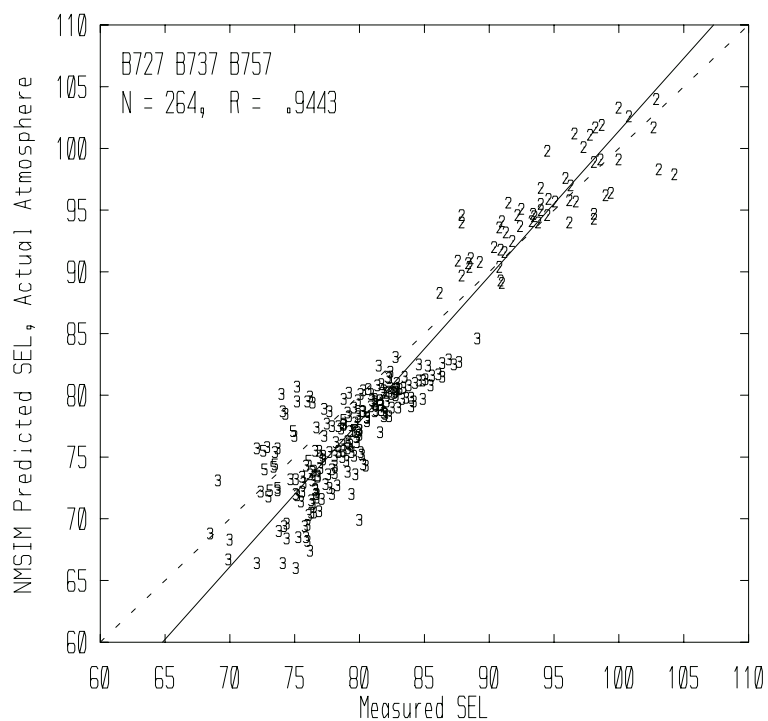
The analysis presented in Section 2 used nominal air absorption. INM uses NPD curves which are calculated via absorption defined in SAE 1845<sup>8</sup>, which nominally corresponds to 59 degrees F, 70 percent relative humidity and sea level pressure. The 1845 absorption coefficients are special to that procedure, and do not correspond to any other standard. NMSIM calculates absorption using the current ANSI standard molecular relaxation procedure<sup>9</sup> at user-specified temperature and humidity. For the calculations presented in Section 2, 59 degrees F and 70 percent humidity were used.

To test the importance of actual temperature and humidity, NMSIM SEL calculations were revised using the actual temperature, humidity and pressure profiles. In Reference 1, profiles had been prepared for each flight, from NOAA upper air soundings, for purposes of calculating performance. In the revised NMSIM calculations, those profiles were used in a stratified atmosphere model. Figure 15 shows NMSIM predictions for actual conditions versus measured SEL.

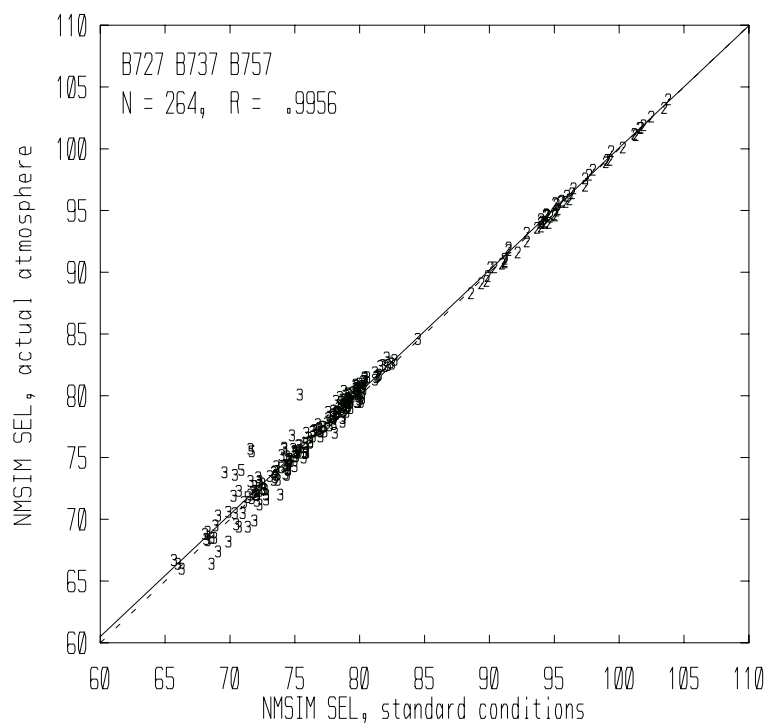
Figure 15 is very similar to Figure 6, which shows NMSIM predictions for standard conditions versus measured SEL. Visually, the regression lines are similar, and the degree of scatter appears similar. The correlation coefficient is very slightly lower for the actual condition calculation, Figure 15. The atmospheric conditions used, however, introduce some scatter. Profiles were based on interpolation of regularly scheduled twice-per-day rawindsonde launches, with some adjustment for surface measurements. While using actual conditions should be an improvement, the addition of another stochastic element leaves scatter about the same.

Differences between the two atmospheric conditions can be seen by direct comparison of the predicted values. Figure 16 shows NMSIM predictions for actual conditions versus predictions for standard conditions. The regression line is close to 1:1, but there is some scatter about the mean. The magnitude of this scatter is seen in Figure 17, which shows the differences between the two as a function of measured SEL. Note that scatter among 727 data is smaller than for 737 data, and 737 data are scattered more at lower SEL. (Recall that lower SEL generally correspond to greater distances.) That behavior is consistent with the spectral content shown in Figure 11. 737 spectra have a greater proportion of energy at higher frequencies, where absorption is stronger, than do 727 spectra. There is also a slight trend for the mean difference to be higher for 727s, but this is less than 1 dB.

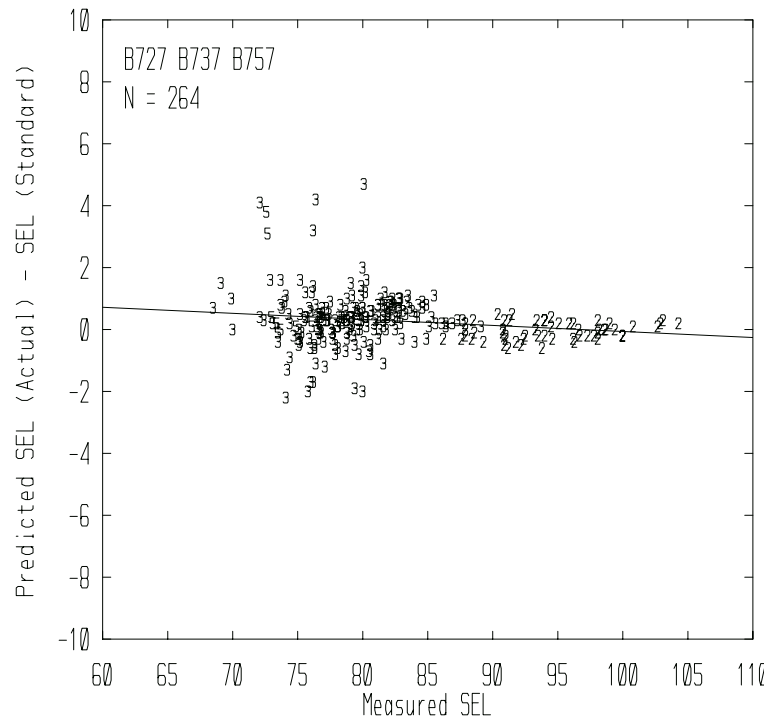
The scatter in Figures 16 and 17 is associated with variability of atmospheric conditions. Moisture content and temperature are the major parameters in air absorption. Figure 18 shows moisture and temperature for the flights being analyzed. These are upper air values (not just surface reports), and correspond to all of the points in the atmospheric profiles used for each flight. Figure 18a shows moisture as relative humidity, and Figure 18b shows moisture as molar concentration of water. Lower temperatures correspond to higher altitudes, where the air is also dryer. (The altitude range in this study is about 5000 feet to 10000 feet MSL.) A point corresponding to the standard condition of 59 degrees F, 70%



**Figure 15. Comparison Between SEL Predicted for Actual Atmospheric Conditions and Measured SEL**



**Figure 16. Comparison Between SEL Predicted for Actual Atmosphere and SEL Predicted for Standard Conditions**



**Figure 17. Difference Between Actual Atmosphere and Standard Condition SEL Predictions**

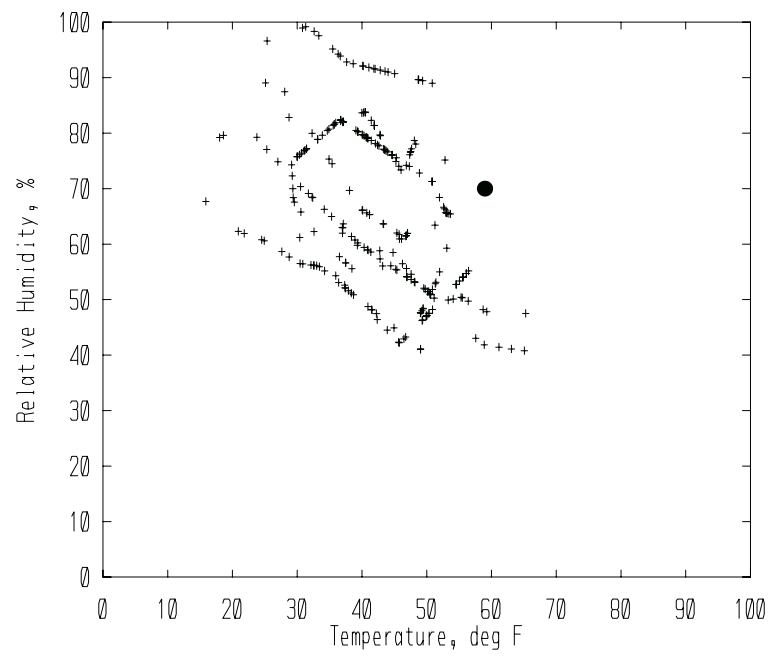
relative humidity is indicated. Note that this reference condition is outside of the envelope of actual flight conditions. The reference condition is also at sea level, ambient pressure 1013 mbar, while at the higher altitudes of the actual conditions ambient pressures were in the range 640 to 820 mbar.

Figure 19 shows absorption coefficients, dB per 1000 feet, as a function of frequency for several conditions:

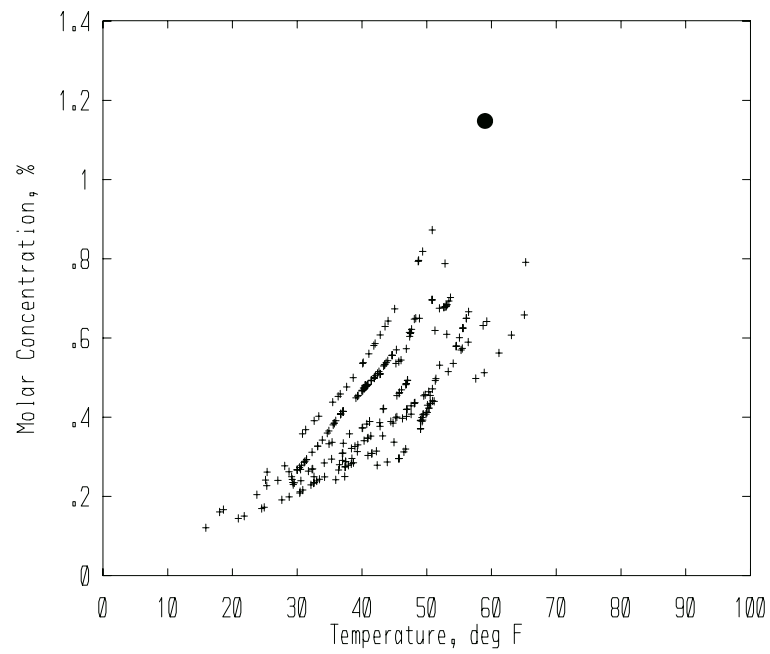
- Standard 59 degrees F, 70% relative humidity, calculated via ANSI standard
- Average actual condition, calculated via ANSI standard
- Maximum and minimum actual condition
- SAE 1845 specification

Two plots are shown: Figure 19a has an absorption range of 0 to 30 dB/1000 feet, and Figure 19b has an absorption range of 0 to 5 dB/1000 feet. The expanded range in Figure 19b allows discrimination of absorption below 1 kHz, which is the most important frequency range after propagation to the ground. Absorption climbs sharply in the upper part of the 100 Hz to 1 kHz range, and very sharply above 1 kHz. This may explain the smaller variability in 727 data (spectral peak 125 to 160 Hz) relative to 737 data (spectral peak 400 to 800 Hz).

In Figure 19b it can be seen that the SAE 1845 absorption is larger than average actual condition absorption up to about 800 Hz, and is larger than any of the actual absorption values up to about 200 Hz. This indicates that analysis using SAE 1845 absorption will tend to underpredict noise levels. In the frequency range up to 800 Hz, average actual absorption is comparable to standard condition absorption.



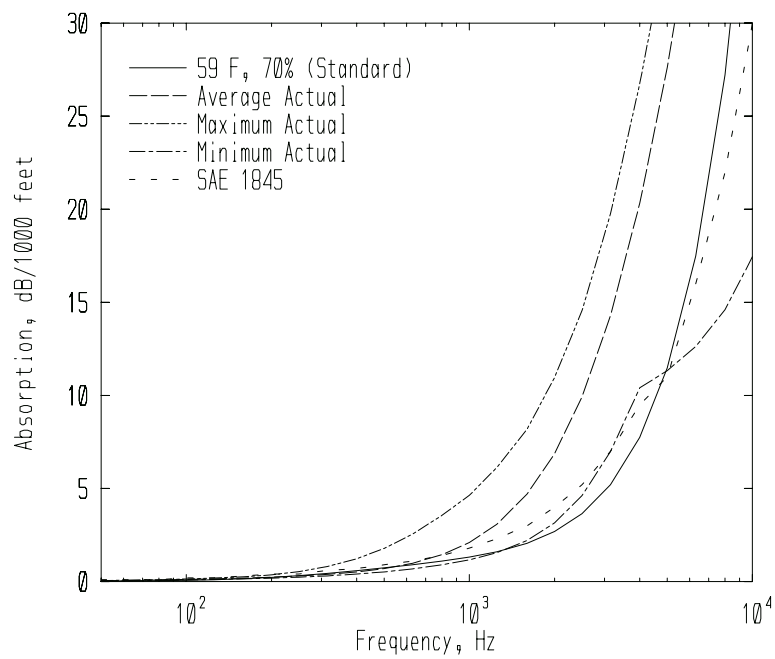
**a. Relative Humidity and temperature**



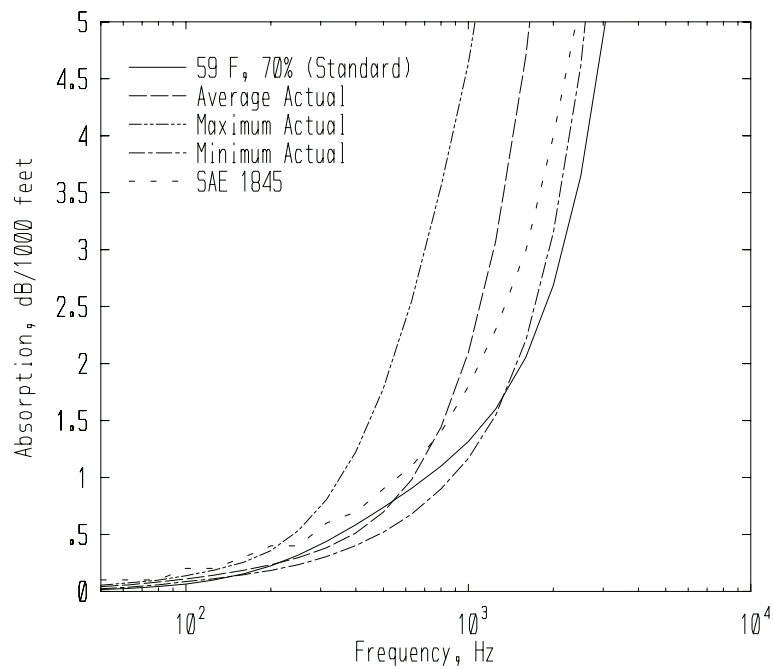
**b. Water Mole Fraction and Temperature**

**Figure 18. Moisture and Temperature for Flight Conditions (+) and Standard Condition (filled circle)**





**a. Full range**

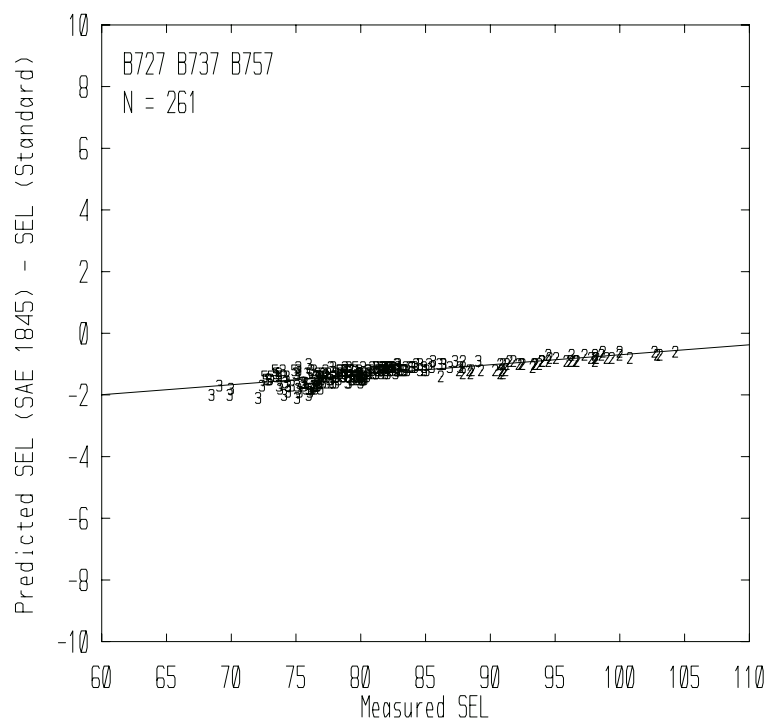


**b. Expanded scale, showing lower frequencies**

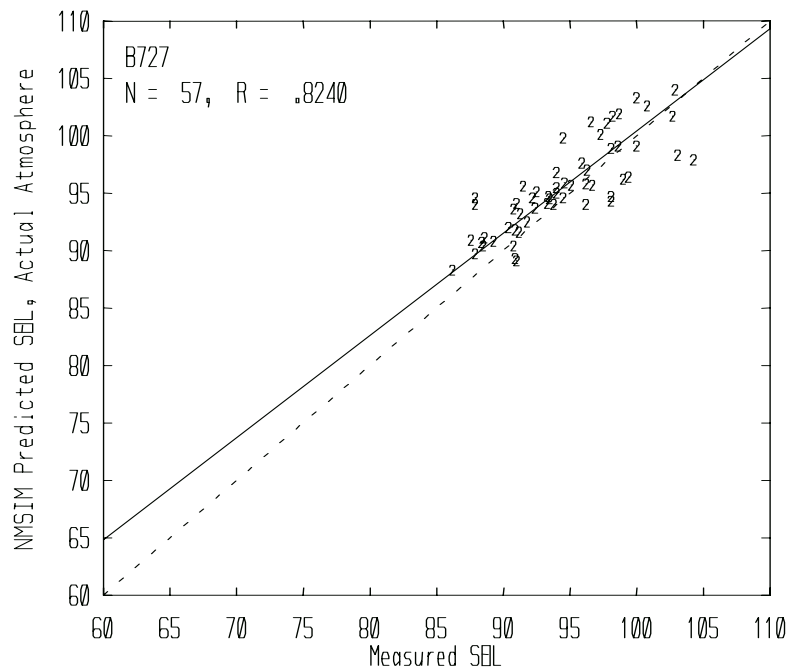
**Figure 19. Absorption Coefficient for Standard Conditions, and Flight Conditions**

Figure 20 shows the difference between SEL predicted for SAE 1845 absorption and SEL predicted for standard conditions. There is a clear trend, with 737 long distance predictions about 2 dB lower for 1845 than for standard conditions. Compare this with Figure 17, where average actual condition predictions are close to standard condition predictions. This result is completely consistent with the relationship between the absorption coefficients seen in Figure 19.

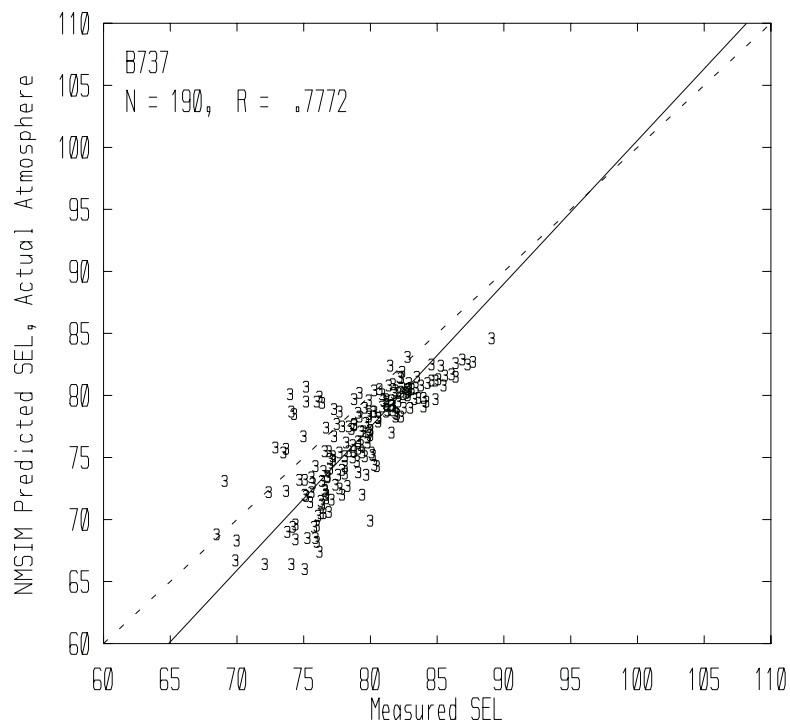
This is consistent with the findings thus far of INM predictions being lower than NMSIM predictions. Comparing Figures 17 and 20, use of the correct atmospheric absorption accounts for 2 to 3 dB of the underprediction of noise for 737s in this data set, and a lesser amount for 727s. Figure 15 represents the best fit of noise modeling to these data. Figures 21 and 22 show these same data, separately for 727s and 737s, respectively. Each separated data set has its own regression fit. The average prediction for 727s is very close to measurements (within 1 dB). The average predictions for 737s is about 2 to 3 dB lower than measurements. It is difficult to say whether there is a definite trend with distance, but scatter is larger for the 737s at lower levels.



**Figure 20. Difference Between SAE 1845 and Standard Condition SEL Predictions**



**Figure 21. Predicted SEL for 727s, Using Actual Atmosphere**



**Figure 22. Predicted SEL for 737s, Using Actual Atmosphere**

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It is also difficult to say why the final results for 737s are low. Analysis was performed with the assumption that the NMSIM source model could be calibrated to NPD values at standard conditions. That worked for the 727s, but not as well for 737s. It is difficult to speculate on the causes of this – tolerances in uncorrected atmospheric conditions and variations in test site ground impedance are possibilities.

Despite the residual 2 to 3 dB for 737s, the final results in Figures 15, 21 and 22 are considerably better than the prior results, Figure 2, which had been based on direct use of INM without adjustment for actual atmospheric effects. The difference has been more than halved.

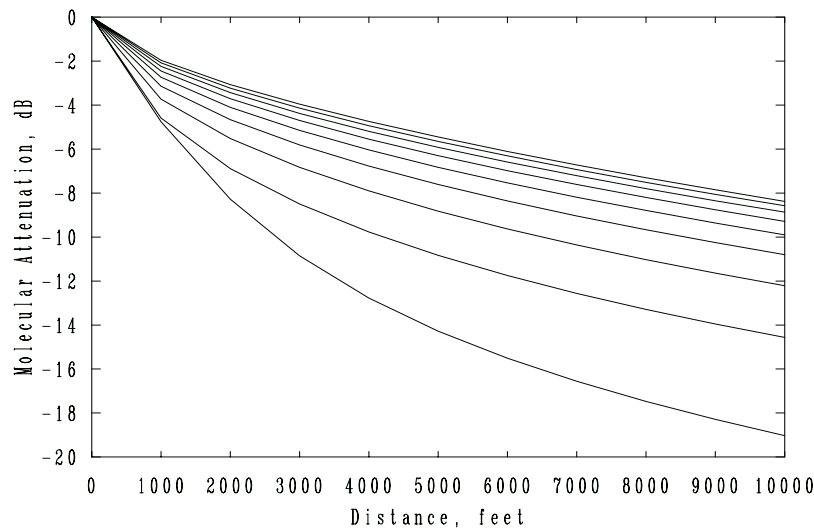
The improvement associated with using correct air absorption has, thus far, been demonstrated for conditions during the May 1997 measurements at Denver. This is one range of conditions. Section 3.2 presents a sensitivity analysis of the effect of absorption over wider conditions.

### **3.2 Sensitivity of Noise Modeling to Absorption**

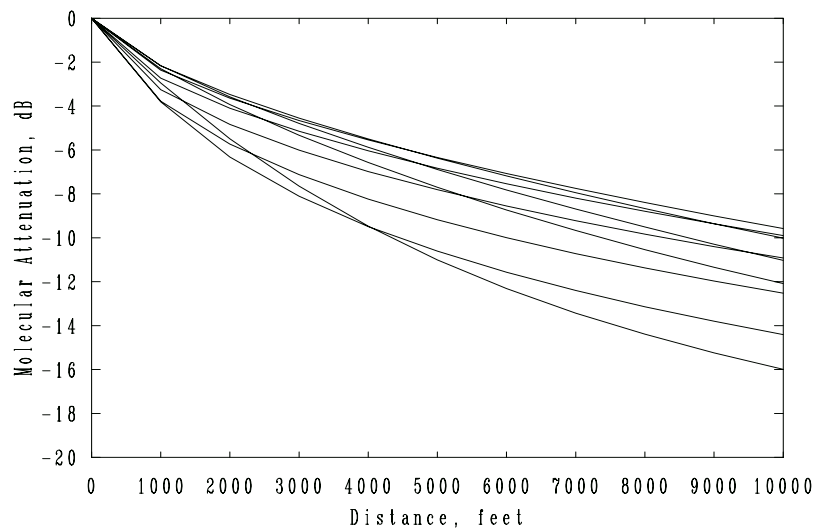
The analysis in Sections 2 and 3.1 showed that air absorption can be a significant factor in accurate modeling of aircraft noise. The analysis, by its nature, was limited to the range of conditions for the specific flights analyzed.

Figures 23 and 24 show the attenuation of A-weighted noise from a typical jet aircraft over a wide range of temperature and humidity. For an aircraft at modest altitudes of 2000 to 5000 feet, changes in either temperature or humidity can easily cause changes of 5 dB in sound level.

Figures 23 and 24 illustrate the potential range, but actual expectations depend on real atmospheric data. Upper air data are collected worldwide at reporting stations that launch weather balloons at noon and midnight GMT. During May at Denver, that corresponds to 6 am and 6 pm local time. Upper air data in the United States are archived, and are available free from NOAA via Internet download, or for a nominal fee via tape or custom download. During the 1997 measurements, upper air data were obtained for May and June at Denver.



**Figure 23. Attenuation of a Point Source Nominal Aircraft Spectrum at 40 degrees F, Relative Humidity 10 Through 90 percent. 10 and 20 Percent (two lowest curves) are Rare Except in the Desert**

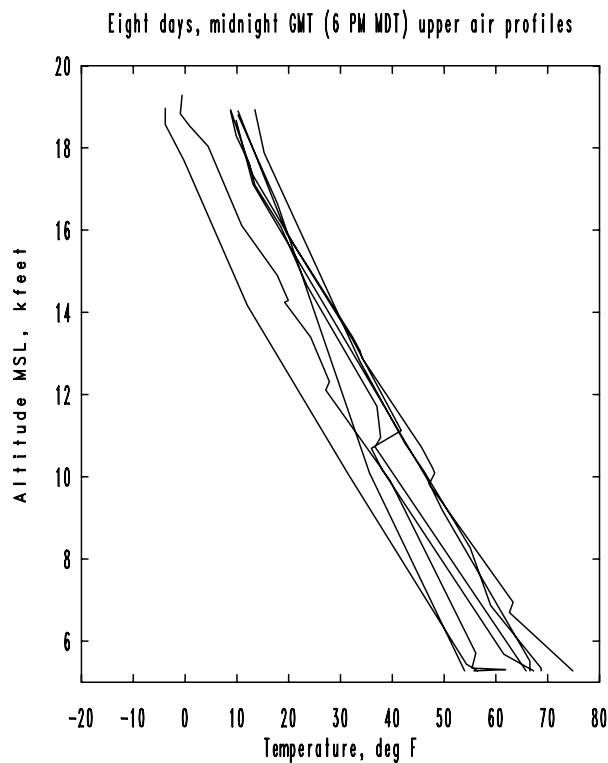


**Figure 24. Attenuation of a Point Source Nominal Aircraft Noise Spectrum at 50 Percent Relative Humidity and Temperatures from 0 to 80 Degrees F**

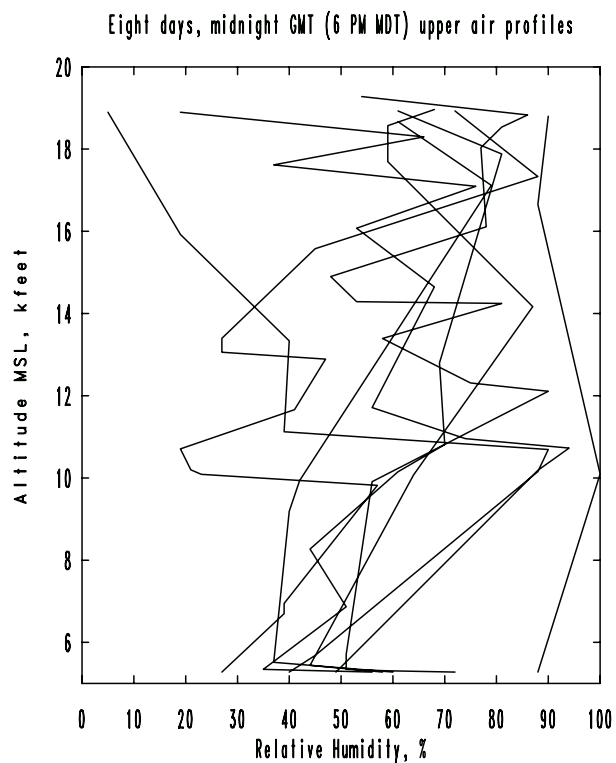
Figures 25, 26 and 27 show typical upper air profile plots. Shown in Figure 25 and 26 are temperature and relative humidity profiles from a series of midnight GMT soundings at Denver. These were during the same period as the flights analyzed in Sections 2 and 3.1. Note that the humidity profiles cover a slightly wider range than seen in Figure 18a for flight times, even dropping below 20 % just above 10,000 feet.

While moisture content is commonly reported as relative humidity, molecular absorption mechanisms are closely related to molar concentrations. Figure 27 shows water molar concentration profiles for the same days. Note that molar concentration behaves more regularly than relative humidity, which depends on both absolute moisture content and temperature. A similar relation is seen in Figures 18a and 18b.

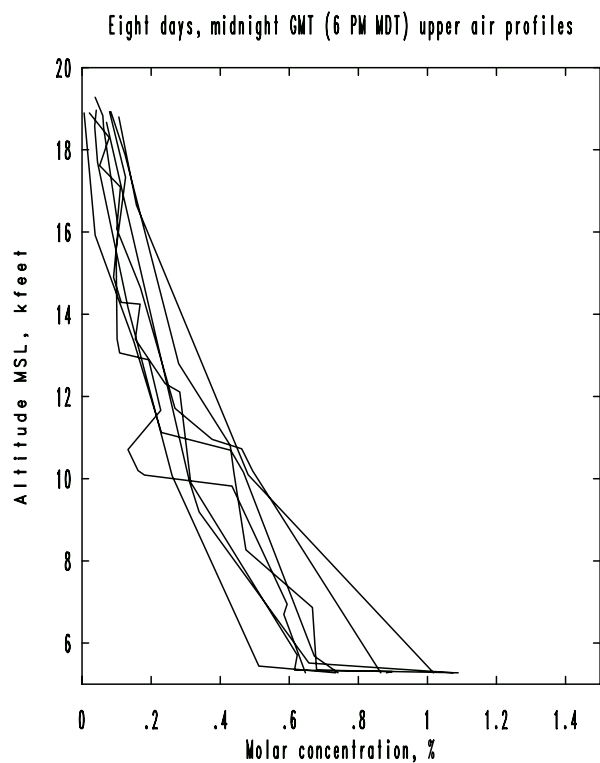
Figure 28 shows the absorption coefficient, dB per 1000 feet, computed for these eight profiles via the ANSI standard at 500 Hz. Shown for comparison is the SAE 1845 absorption at the same frequency. Note that actual absorption of 500 Hz is lower than SAE 1845 absorption up to about 5000 feet AGL. This is consistent with the INM underprediction trend seen in the current data. General implications of atmospheric conditions must, however, be based on a statistically broad analysis.



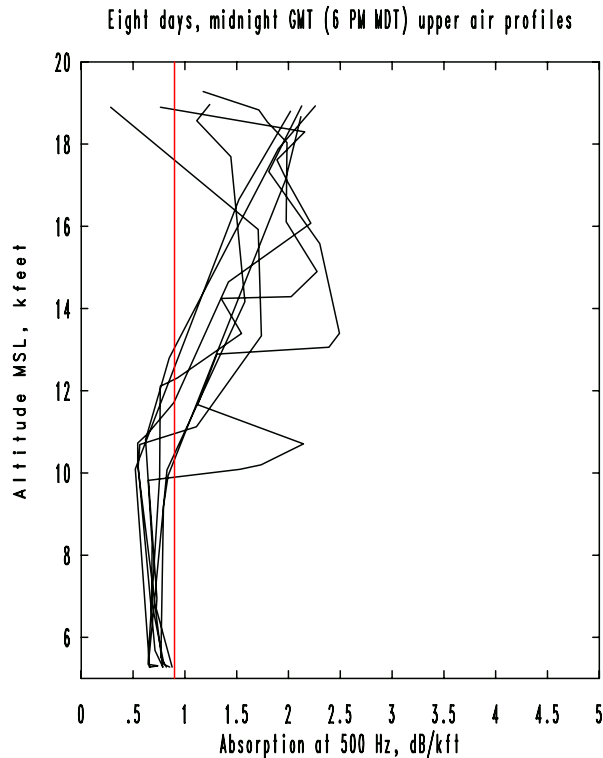
**Figure 25. Upper Air Temperature Profiles, Midnight GMT (6 pm MDT) Soundings, Eight Days at Denver**



**Figure 26. Upper Air Relative Humidity, Midnight GMT (6 pm MDT) Soundings, Eight Days at Denver**



**Figure 27. Upper Air Water Molar Concentration Profiles, Midnight GMT (6 pm MDT) Soundings, Eight Days at Denver**



**Figure 28. ANSI Absorption at 500 Hz, Compared to SAE 1845 Absorption, Eight Days in Denver**

### 3.3 Atmospheric Variability Across the United States

There are about 100 upper air sounding stations in the United States that collect twice-daily rawindsonde data. Measurements are made of pressure, temperature, dew point, wind direction and wind speed at a number of altitudes. Data are typically recorded at 40 to 60 altitudes from surface to about 100,000 feet.

Data for year 2000 were obtained for seven stations, each at or near a major air carrier airport. Stations were chosen at or near Denver, Atlanta, Dallas-Fort Worth, Washington Dulles, Miami, Minneapolis-St. Paul, and San Francisco airports. Table 2 lists the seven stations, with their codes, coordinates and ground elevation. These seven were selected as representing a range of geographic locations and regional climates.

The upper air profiles are taken twice a day, at noon and midnight GMT. At the seven locations in Table 2, that corresponds to local times between 4 and 8 am and pm. The noon GMT sounding is morning local time, and the midnight sounding is afternoon local time. Those are generally very useful periods for atmospheric sound propagation considerations: morning soundings will give conditions without solar heating, while afternoon soundings will give conditions with the day's accumulation of solar heating. The range of diurnal variation is thus bracketed.



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**Table 2. Upper Air Sounding Stations Selected for Analysis**

<b>City/Airport</b>	<b>Station Code</b>	<b>Latitude</b>	<b>Longitude</b>	<b>Altitude, Feet MSL</b>
Denver, Colorado	DEN	39.77	-104.88	5285
Peachtree, Georgia	FFC	33.35	-84.56	807
Fort Worth, Texas	FWD	32.80	-97.30	643
Dulles, Virginia	IAD	38.98	-77.47	279
Miami, Florida	MFL	25.75	-80.38	13
Minneapolis, Minnesota	MPX	44.83	-93.55	942
Oakland, California	OAK	37.75	-122.22	20

Seasonal variations are also of interest. Since data are collected twice daily, they can be examined over any desired period. For the purposes of this study, they were analyzed by month. Seasonal patterns were seen at all locations, with the greatest differences in patterns occurring (not surprisingly) between January and July. Patterns for months other than January and July generally fell between the patterns for those two months. The month-to-month variations were not necessarily a uniform progression, but they were generally monotonic in nature. Examination of January and July will therefore bracket annual variability.

Figures 29 through 35 show temperature vs. altitude for January and July at all seven stations. Figures 36 through 42 show moisture content vs. altitude. The format of these plots is similar to that of Figures 25 and 27. The molar concentration scale in Figures 36 through 42 is broader than in Figure 27, to accommodate higher moisture content at several of the stations. The temperature and altitude scales are similar to those in Figures 25 and 27, but the origins are shifted by season and station to accommodate significant climactic and ground altitude differences.

A distinct pattern in the temperature profiles is that, in most cases, the day-to-day variability is greater in the winter (top half of each figure) than in the summer (bottom half). The one clear exception is Oakland, where there is no real winter. Summer of 2000 in Oakland also had a persistent inversion layer around 2000 feet.

Each temperature plot includes both morning and afternoon soundings. At higher altitudes, there was little difference between the two. At low altitudes, there was usually an inversion near the ground. This is fairly distinct in the July data in Denver, where about half the curves have a distinct change in slope near the ground. In January in Minneapolis, inversions below 5000 feet were common in both morning and afternoon.

Molar concentration of water vapor does not show any marked patterns. There is generally a trend toward greater moisture content in the summer than the winter. This is distinct in Minneapolis, which has greater differences between summer and winter than any of the

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other stations. Molar concentration in Denver is lower than the other locations, a consequence of Denver's high altitude and dry climate.

Cross-plots of moisture and temperature, in format similar to Figure 18b, are presented in Figures 43 through 49. The general patterns are similar to that seen in Figure 18b: there is typically a wedge-shaped humidity-temperature domain, with the upper limit of moisture corresponding to 100 percent humidity, and the lower bounds of moisture depending on local conditions. In Denver, moisture content can be near zero even when temperatures are high. In the southern and eastern locations, this pattern can occur in the winter but in summer the lower bound of moisture can be parallel to the upper. This is quite distinct in Miami, where summertime humidity falls in a rather narrow (and damp) band, and even winter conditions show a similar trend.

Air absorption has been computed for seasonal temperature and humidity at each of the sounding stations. The procedure was to compute the attenuation of A-weighted level of a 737 full-power spectrum from each altitude to the ground. This was done for each sounding. The calculation is for a point source, but the trend applies to line sources.

Figure 50 shows attenuation based on the absorption in SAE 1845. That attenuation is universal, applicable at all locations and not adjusted for temperature or humidity.

Figures 51 through 57 show attenuation computed, by the ANSI procedure, for each of the upper air profiles presented in Figures 29 through 42. Barometric pressure (not presented in this report, but included in the upper air data) is accounted for. For a given temperature and pressure, absorption is greater at lower pressure. This is a consequence of absorption in the range of interest being primarily due to molecular relaxation processes, and at lower pressure there are fewer molecules and hence fewer collisions.

Absorption results in Figures 51 through 57 are consistent with the temperature and humidity trends seen in the upper air profiles. In most places (Oakland being the exception) variation is much smaller in the summer than the winter. In Miami, where summers are hot and moist, air absorption has very little spread and falls above the SAE 1845 line, i.e., there is less actual attenuation. SAE 1845 attenuation also lies in the lower portion of Denver summer attenuation (i.e., 1845 predicts more attenuation, and lower noise levels), which is consistent with the results shown in Section 3.1.

In general, the SAE 1845 attenuation curve falls within the computed actual attenuation, but (depending on location and season) there can be significant variation about it. At lower altitudes, the spread is relatively small, but at 5000 feet AGL absorption can be up to  $\pm 4$  dB about the average. This can be significant when performing noise model validation studies over a limited period. It also raises the question as to whether these variations would average out over a year's operations, or whether there could be a systematic bias. NOISEMAP addresses this by using local "annual absorption average" temperature and humidity values, but this assumes a symmetric behavior that will average out to zero. The magnitude of variation of absorption suggests that this detail should not be addressed by assumption.

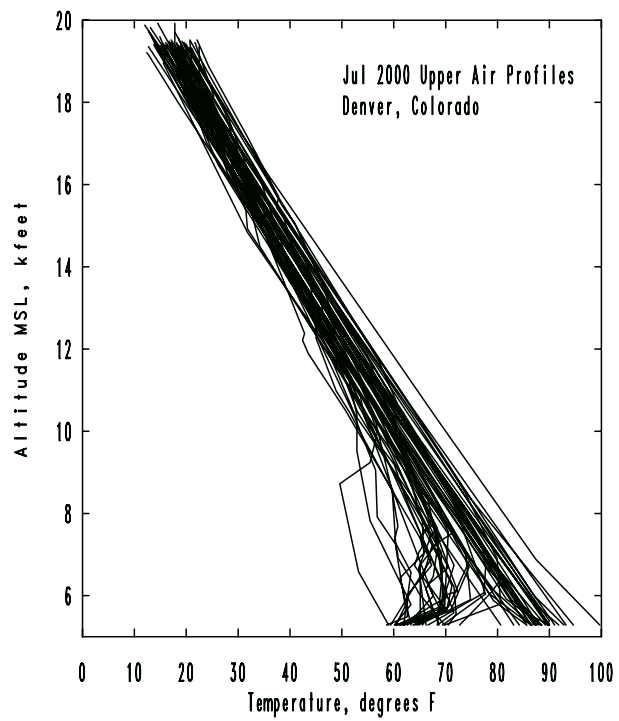
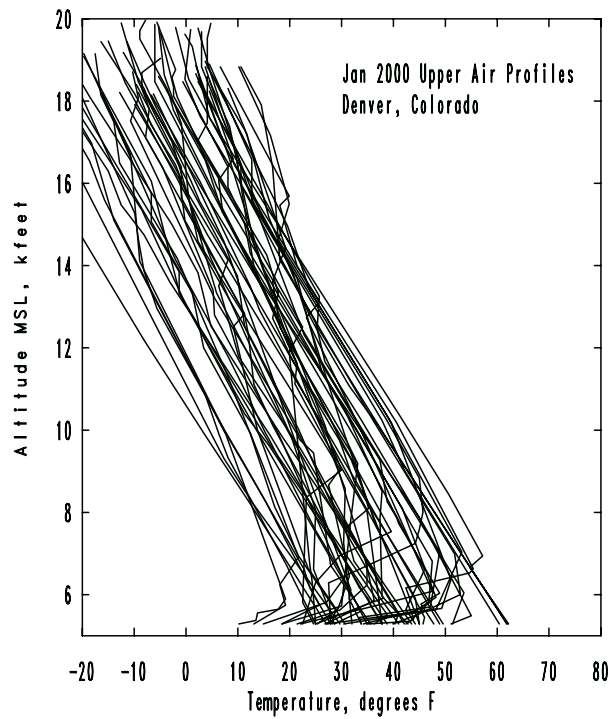


Figure 29. Temperature Profiles at Denver, Winter and Summer

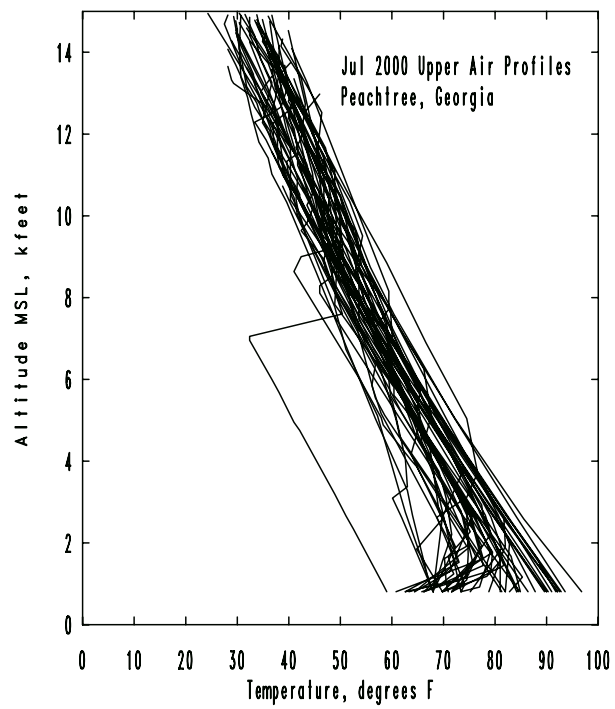
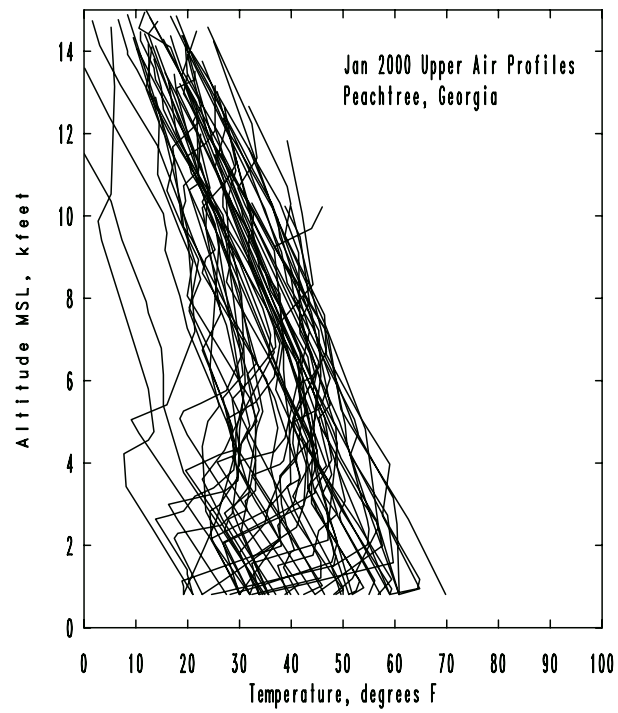


Figure 30. Temperature Profiles at Peachtree, Winter and Summer

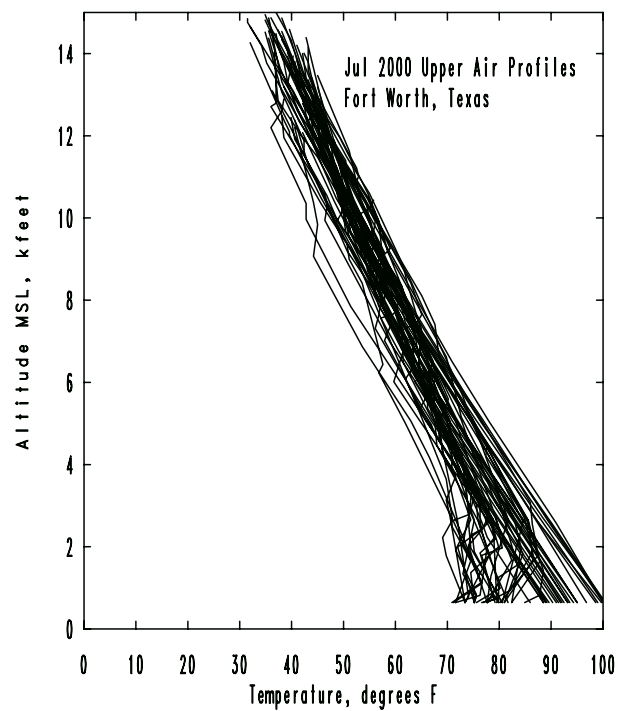
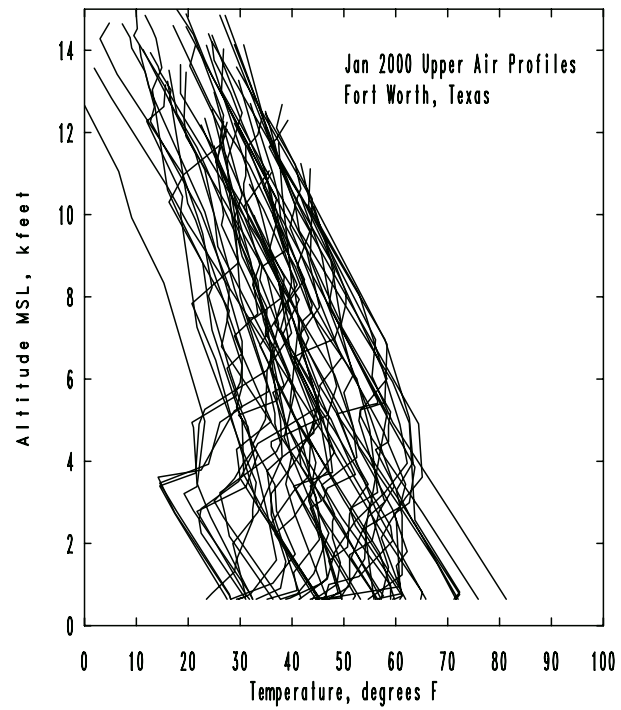


Figure 31. Temperature Profiles at Fort Worth, Winter and Summer

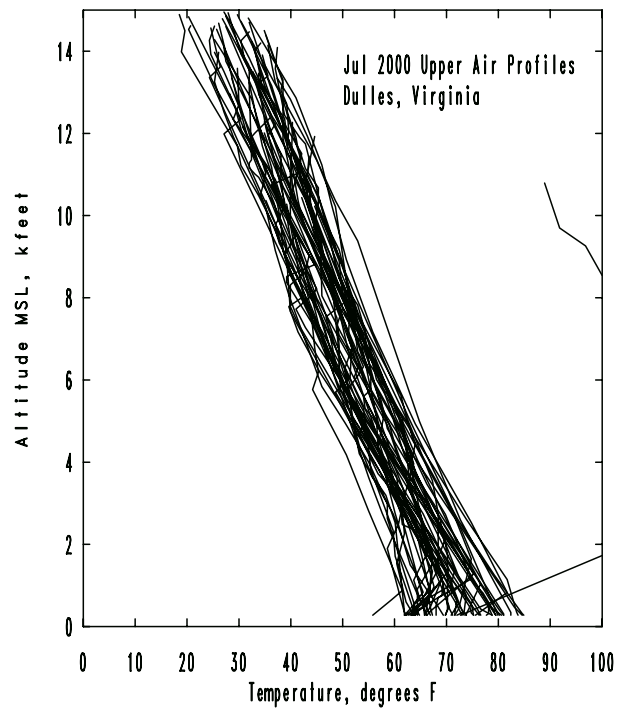
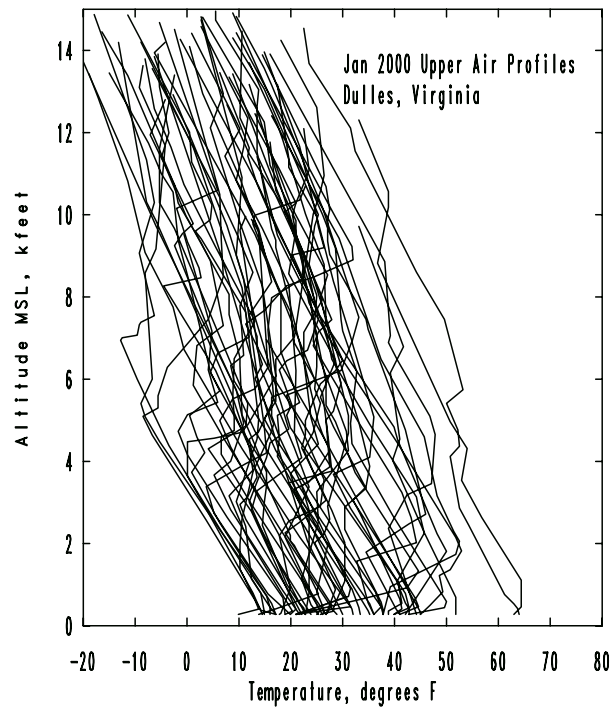


Figure 32. Temperature Profiles at Dulles, Winter and Summer

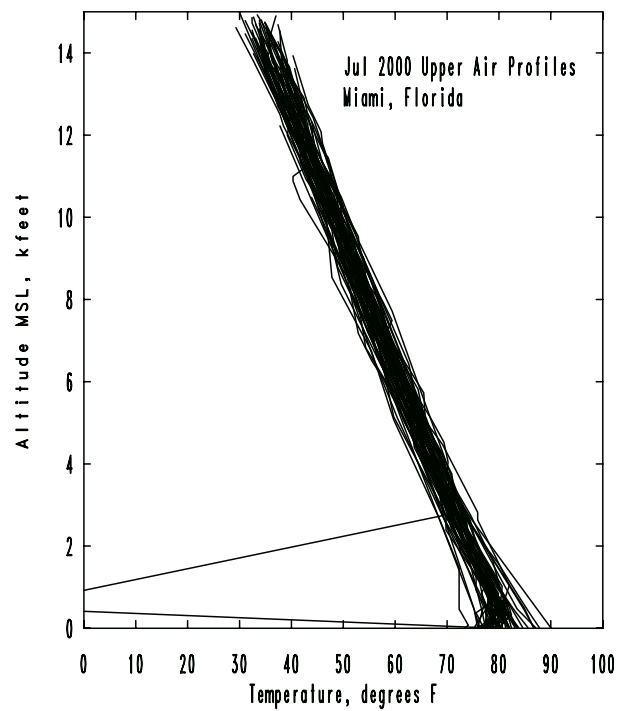
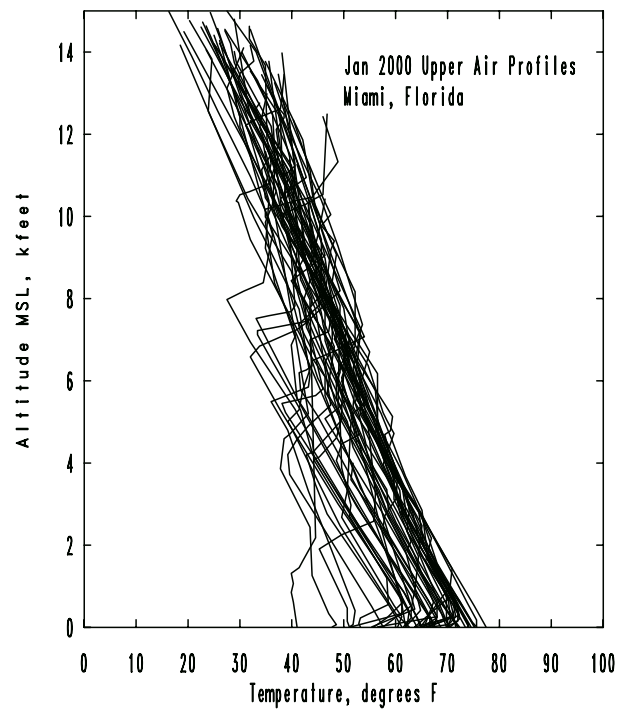


Figure 33. Temperature Profiles at Miami, Winter and Summer

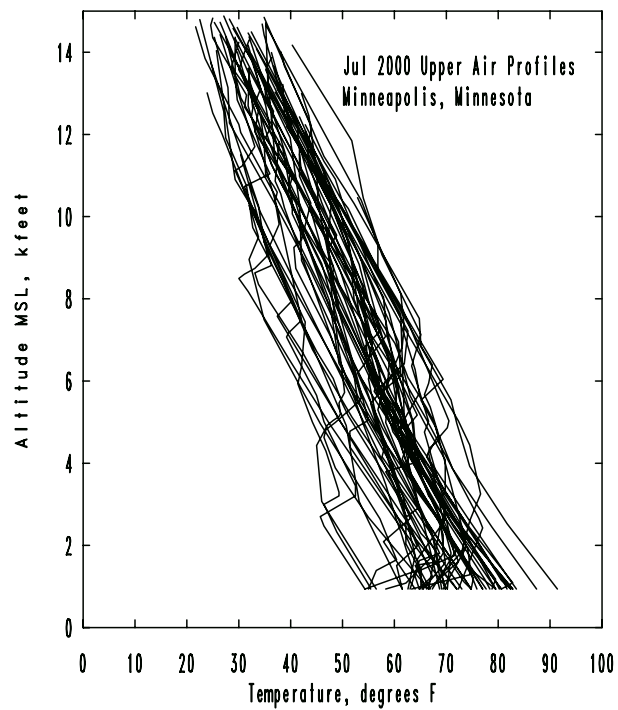
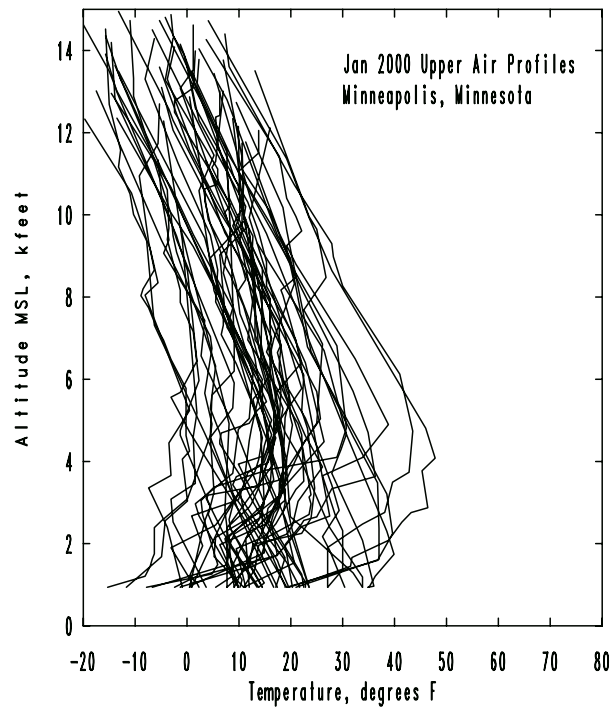


Figure 34. Temperature Profiles at Minneapolis, Winter and Summer



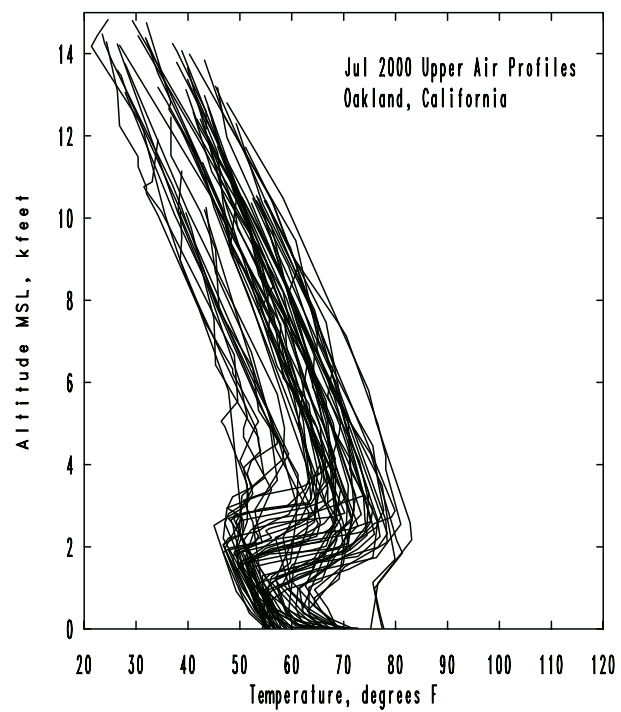
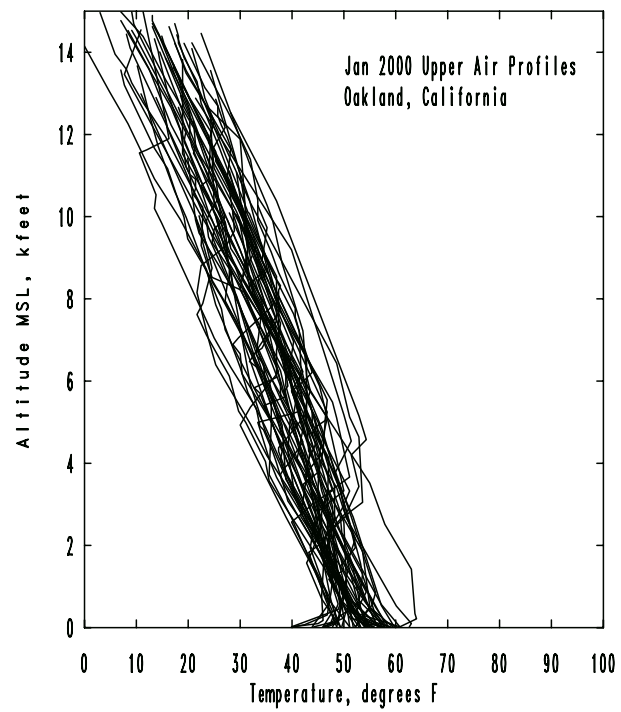


Figure 35. Temperature Profiles at Oakland, Winter and Summer

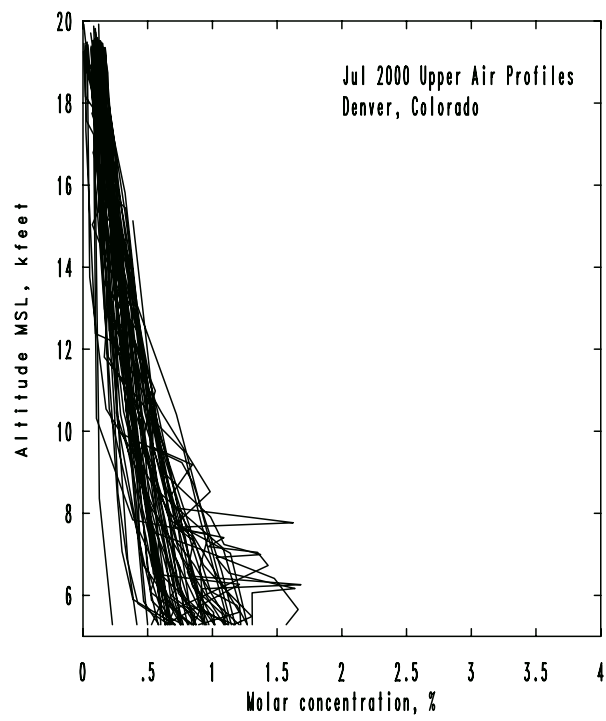
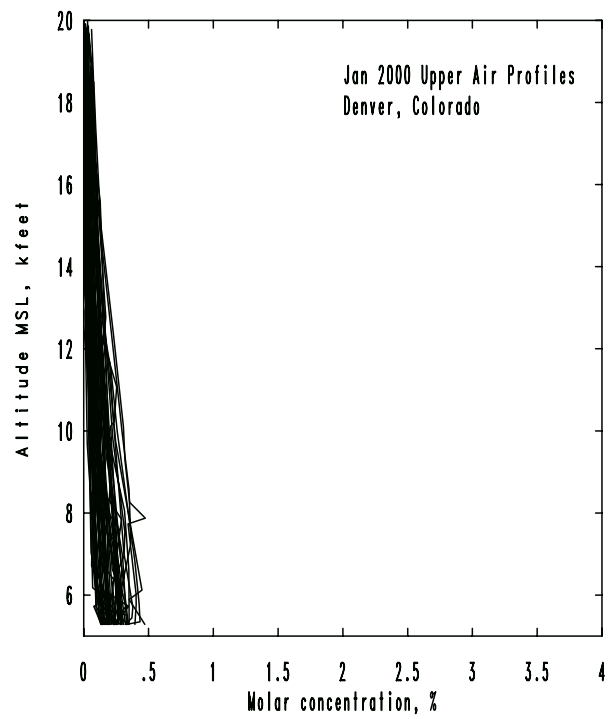


Figure 36. Water Molar Concentration Profiles at Denver, Winter and Summer

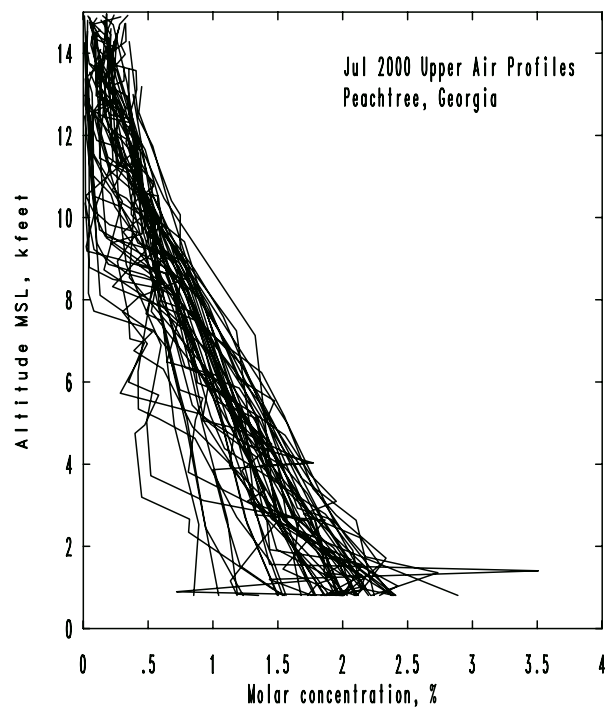
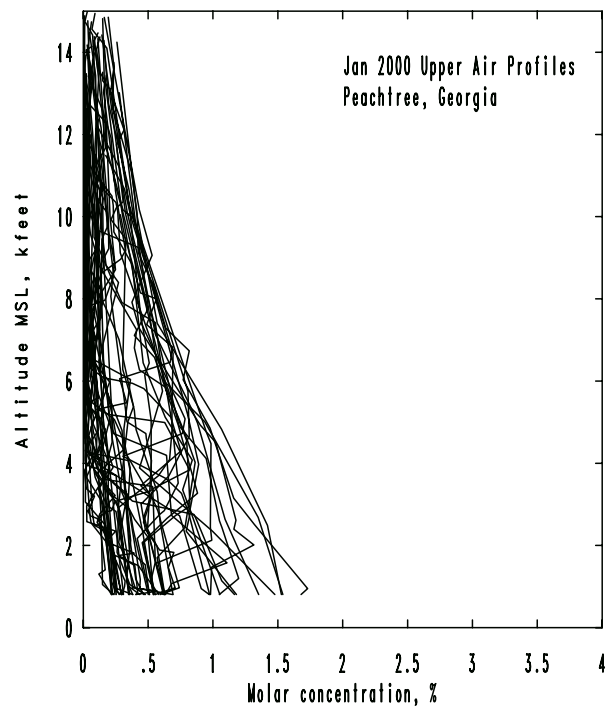


Figure 37. Water Molar Concentration Profiles at Peachtree, Winter and Summer

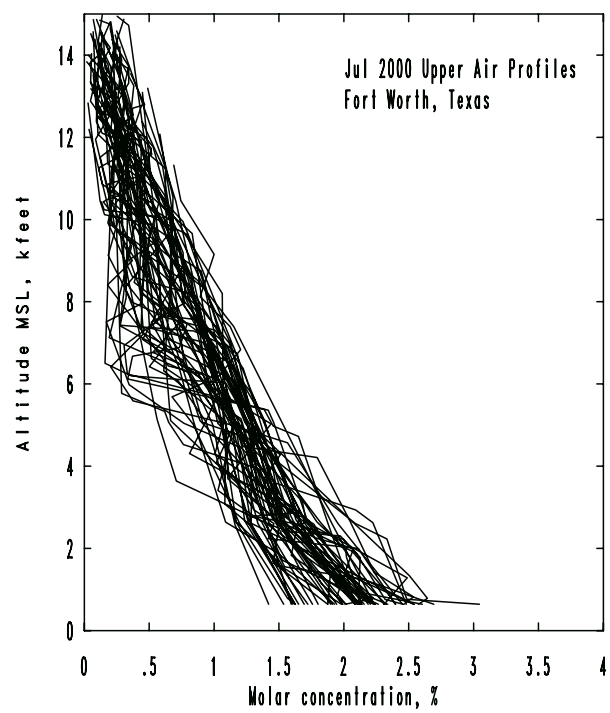
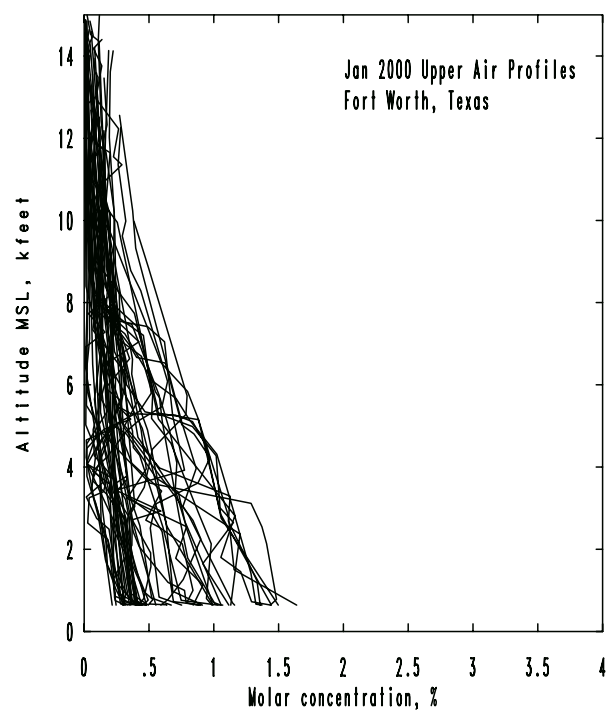


Figure 38. Water Molar Concentration Profiles at Fort Worth, Winter and Summer

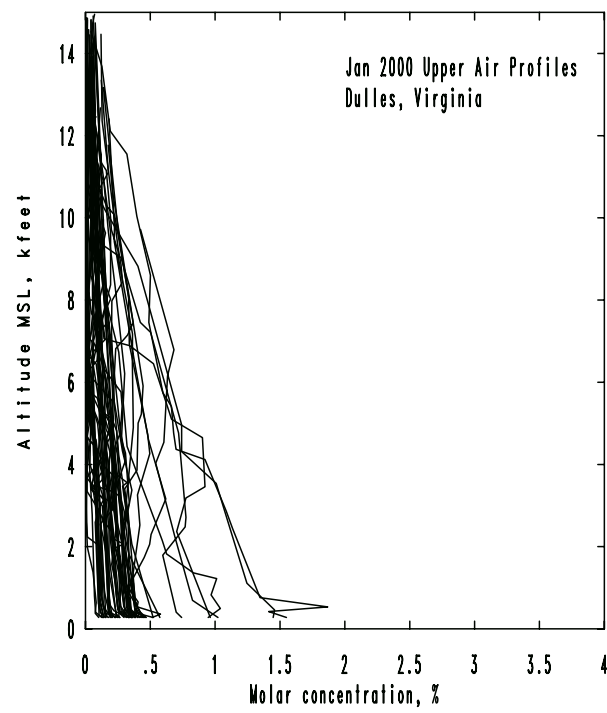
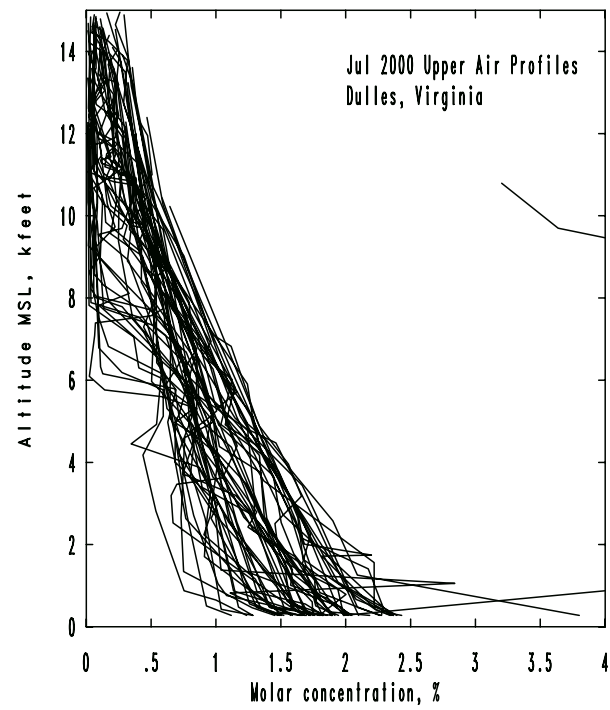


Figure 39. Water Molar Concentration Profiles at Dulles, Winter and Summer

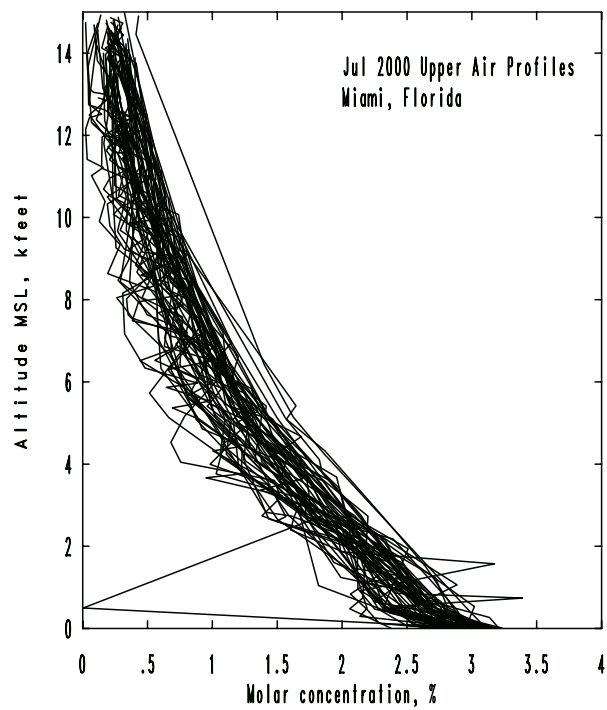
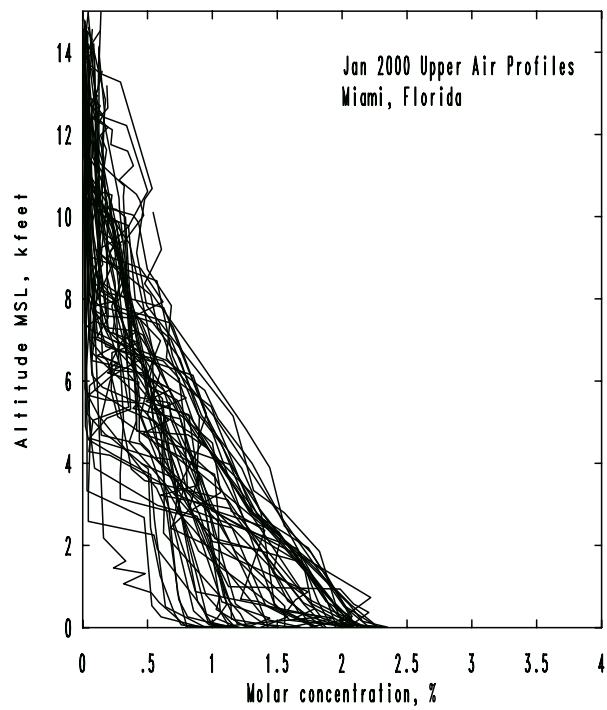


Figure 40. Water Molar Concentration Profiles at Miami, Winter and Summer

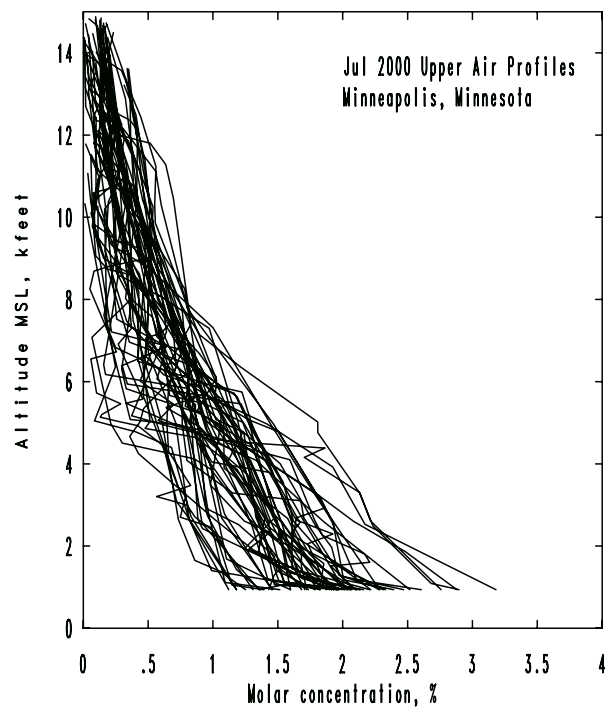
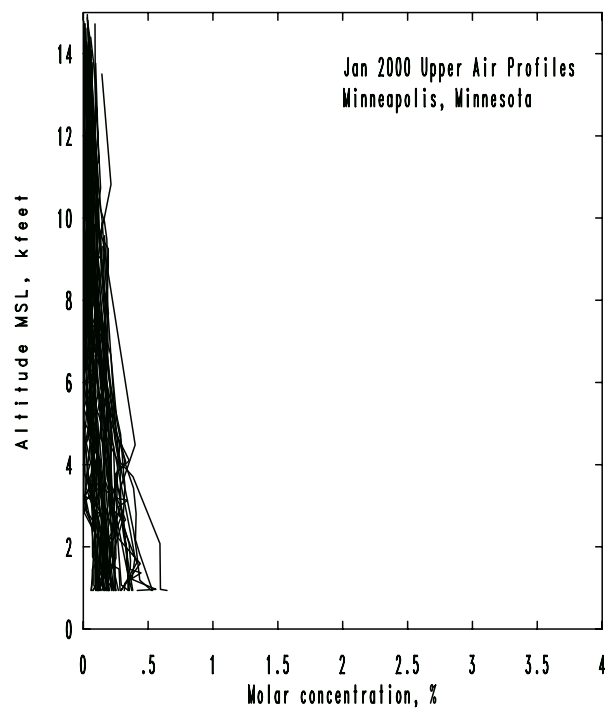


Figure 41. Water Molar Concentration Profiles at Minneapolis, Winter and Summer

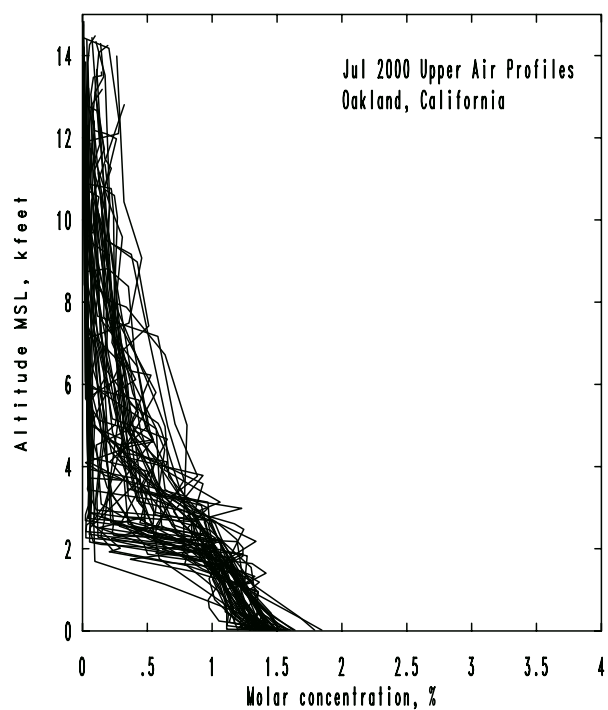
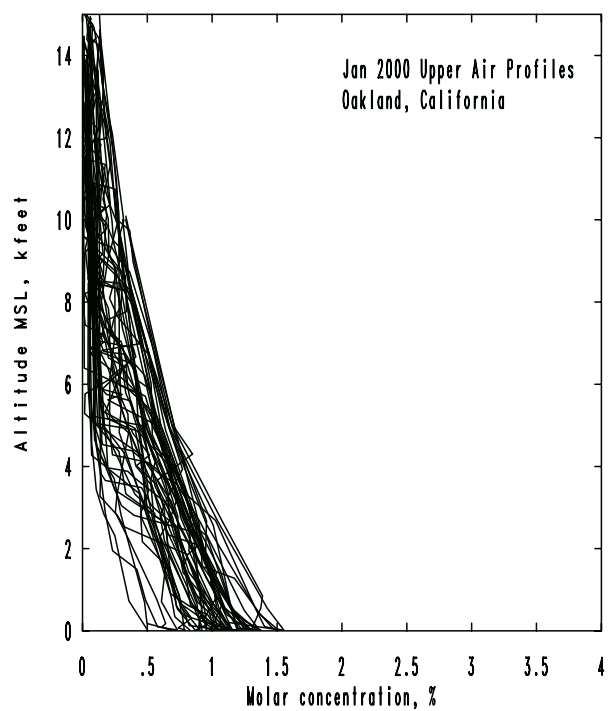


Figure 42. Water Molar Concentration Profiles at Oakland, Winter and Summer



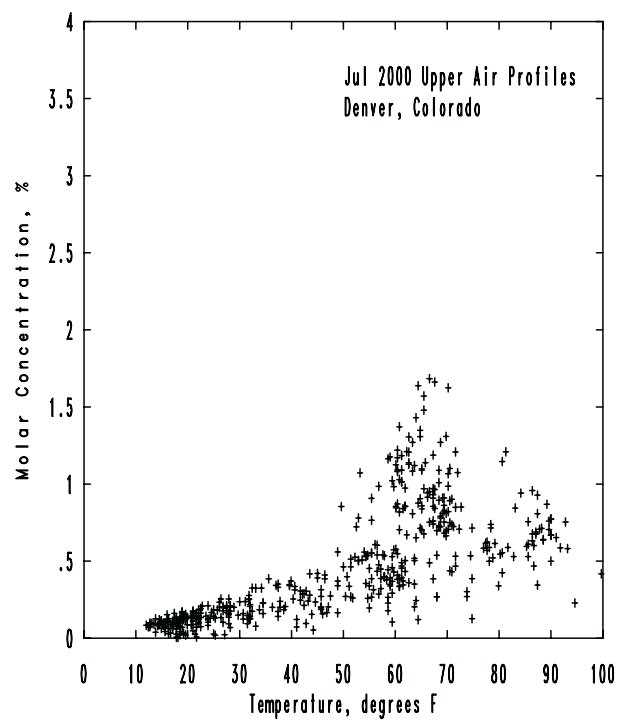
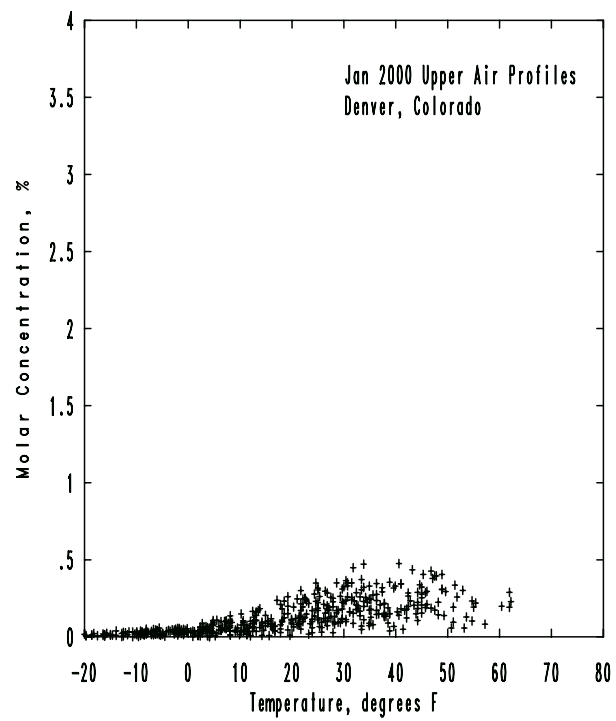


Figure 43. Temperature and Moisture Distribution at Denver, Winter and Summer

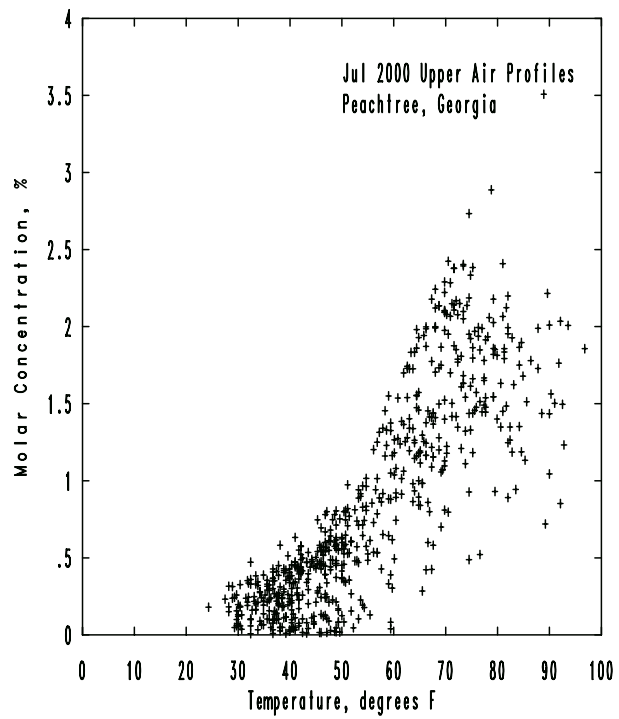
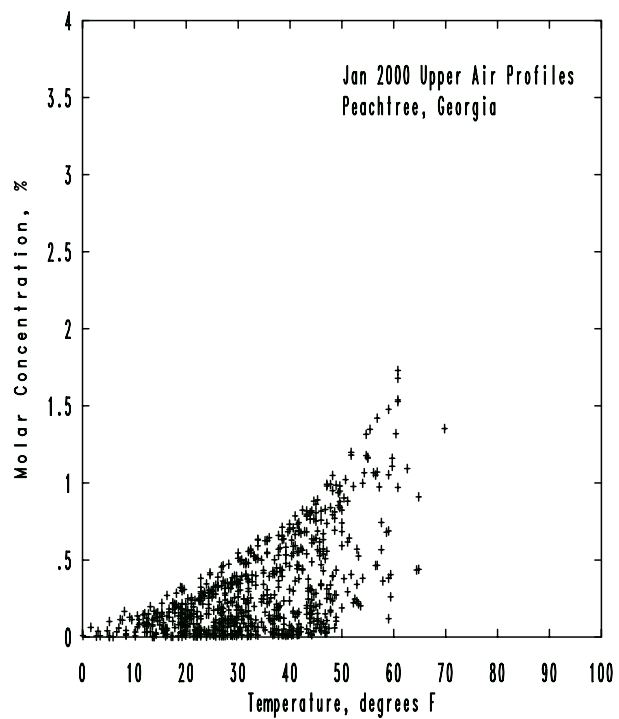


Figure 44. Temperature and Moisture Distribution at Peachtree, Winter and Summer

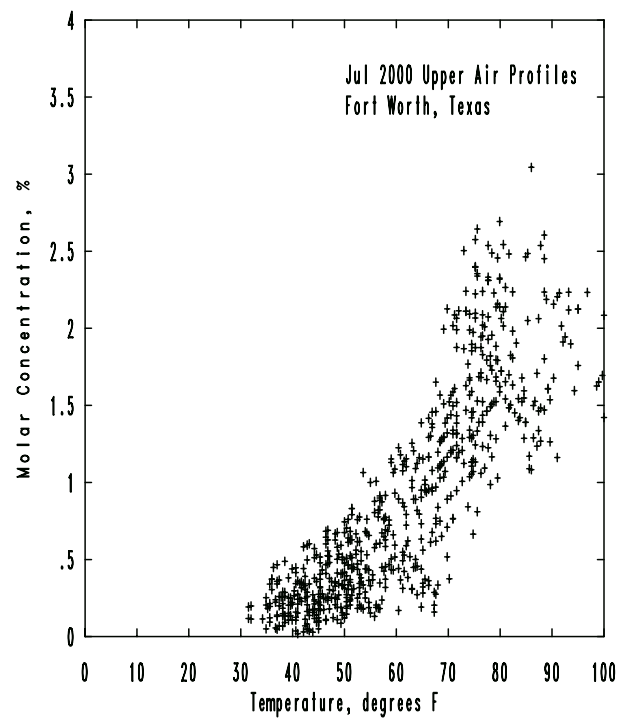
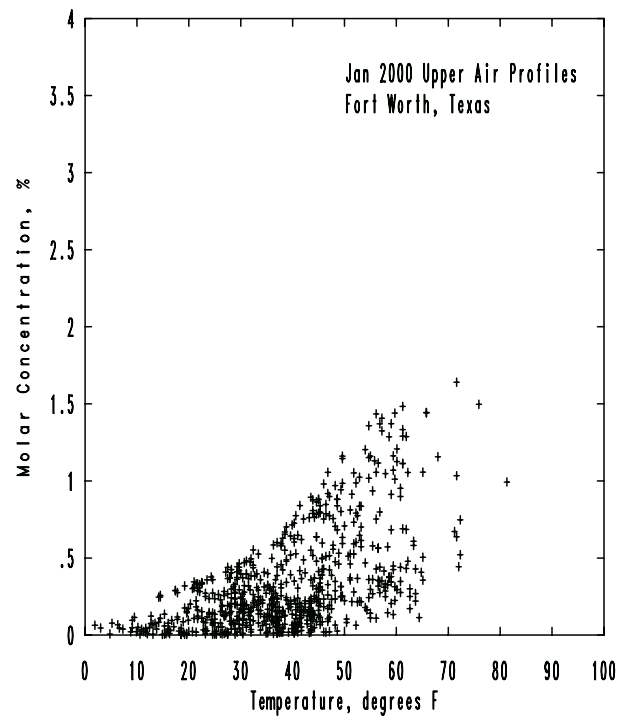


Figure 45. Temperature and Moisture Distribution at Fort Worth, Winter and Summer

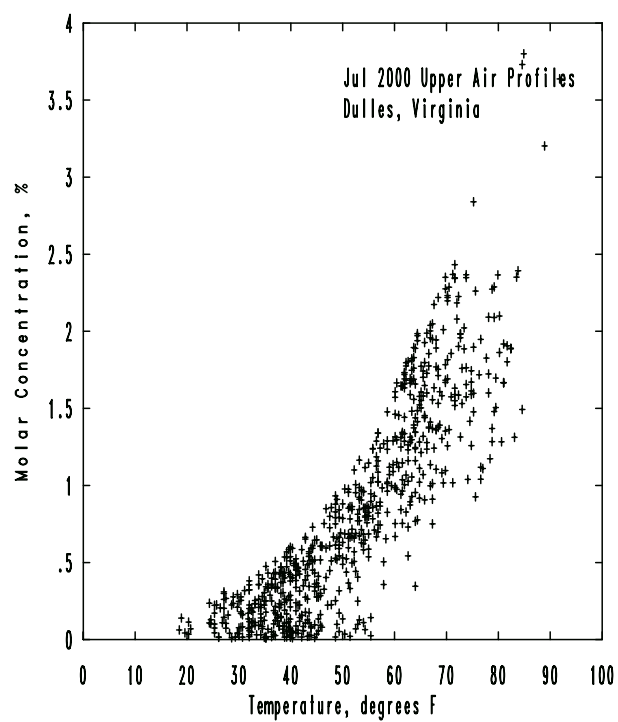
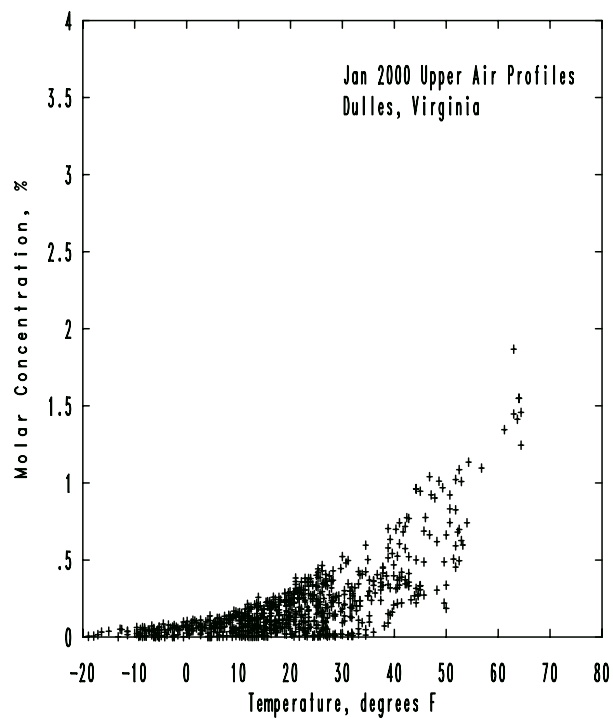


Figure 46. Temperature and Moisture Distribution at Dulles, Winter and Summer

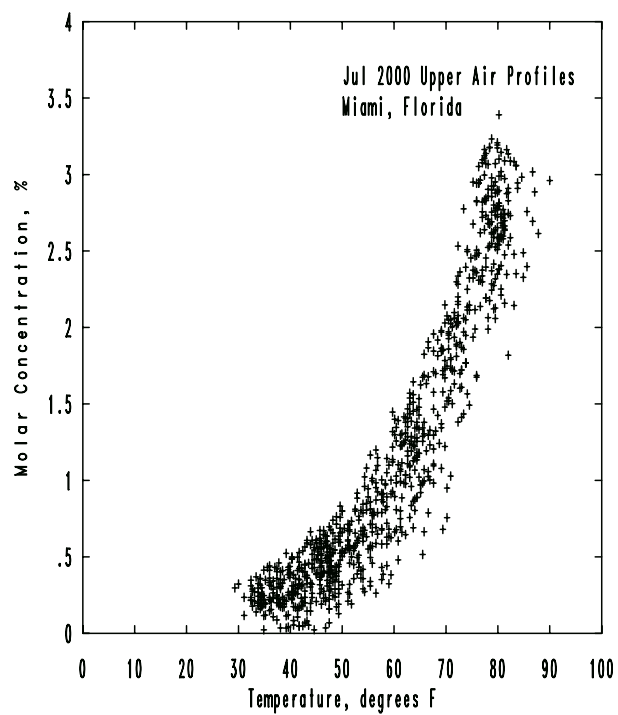
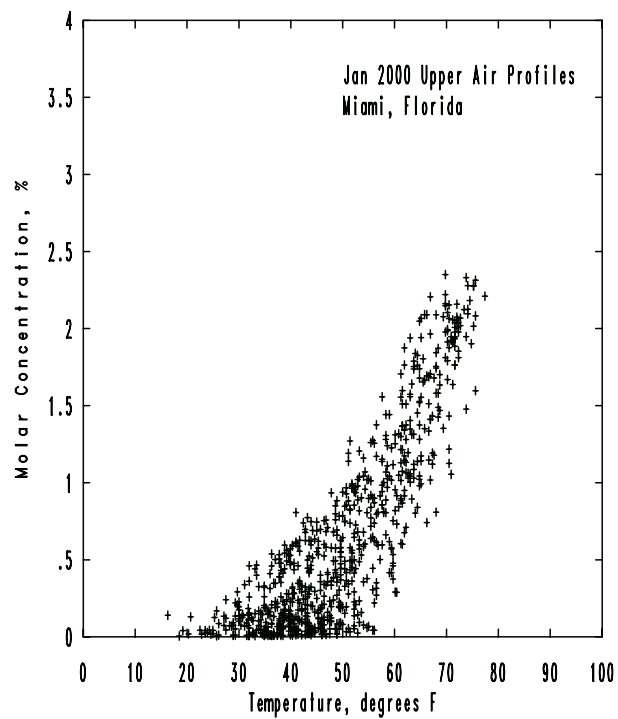


Figure 47. Temperature and Moisture Distribution at Miami, Winter and Summer

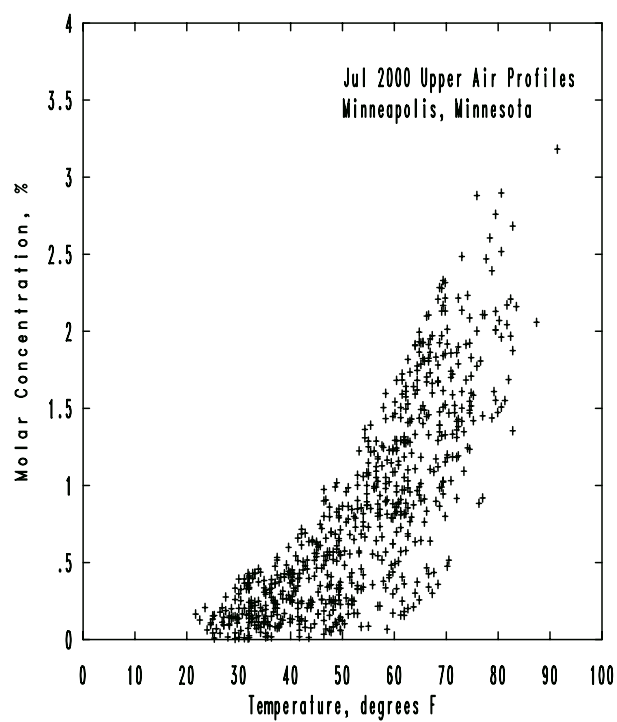
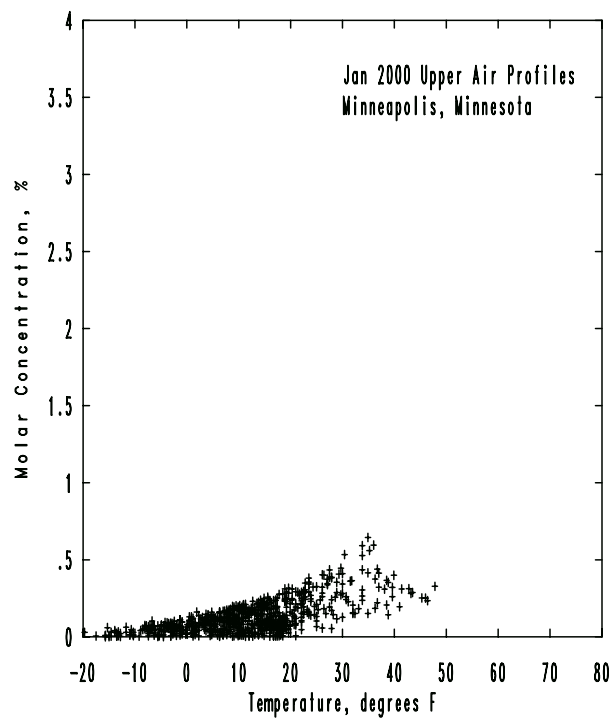


Figure 48. Temperature and Moisture Distribution at Minneapolis, Winter and Summer

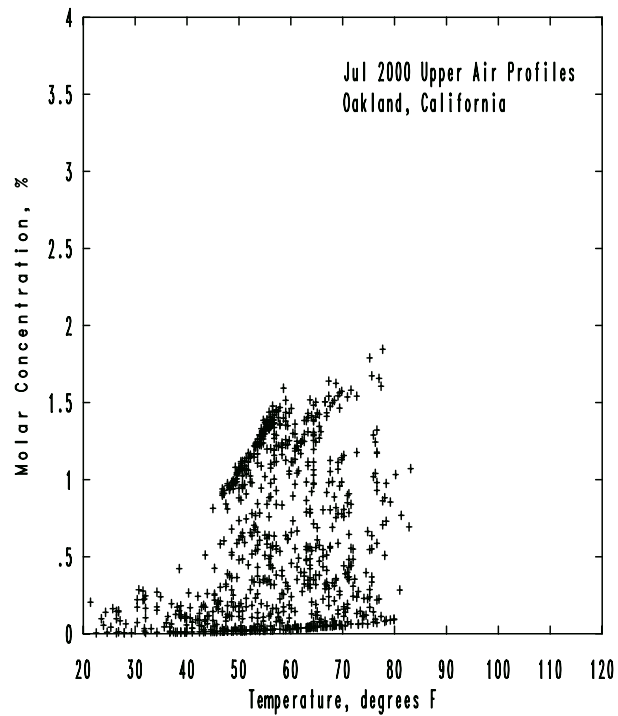
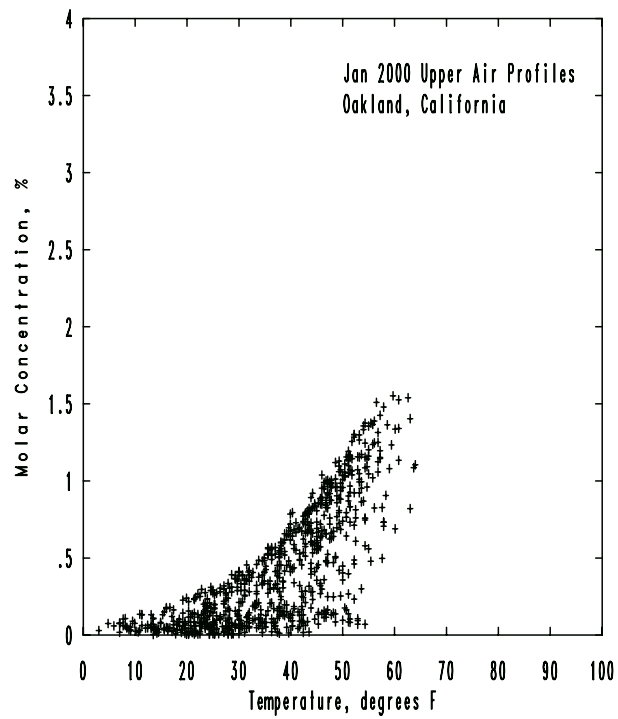
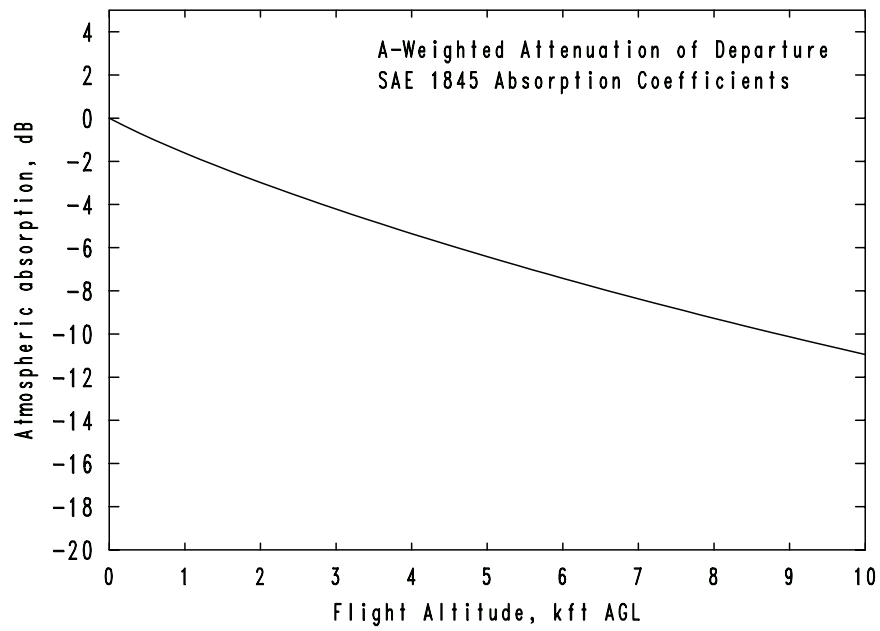
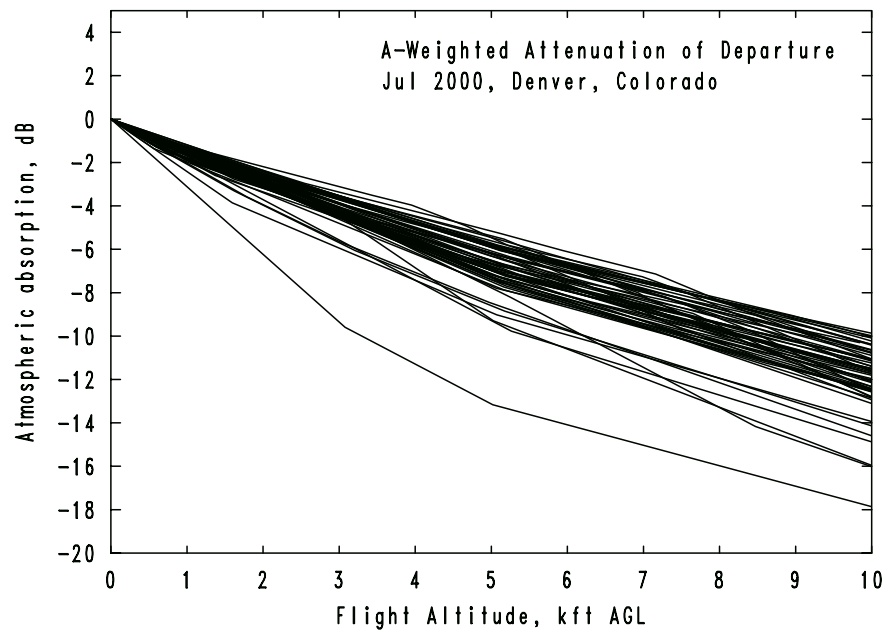
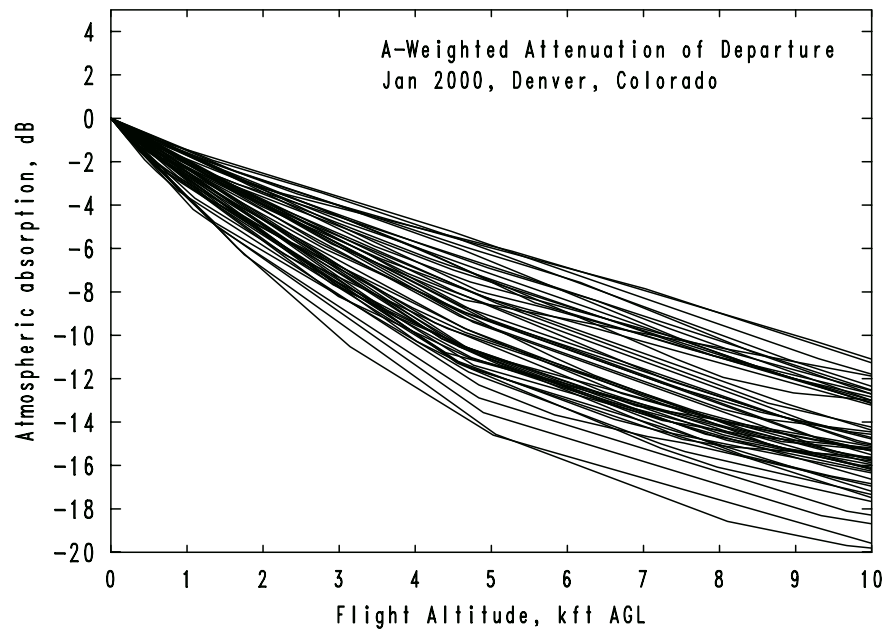


Figure 49. Temperature and Moisture Distribution at Oakland, Winter and Summer



**Figure 50. Attenuation of A-Weighted Level from 737, SAE 1845 Absorption**





**Figure 51. Attenuation of A-Weighted Level from 737, Denver Winter and Summer**

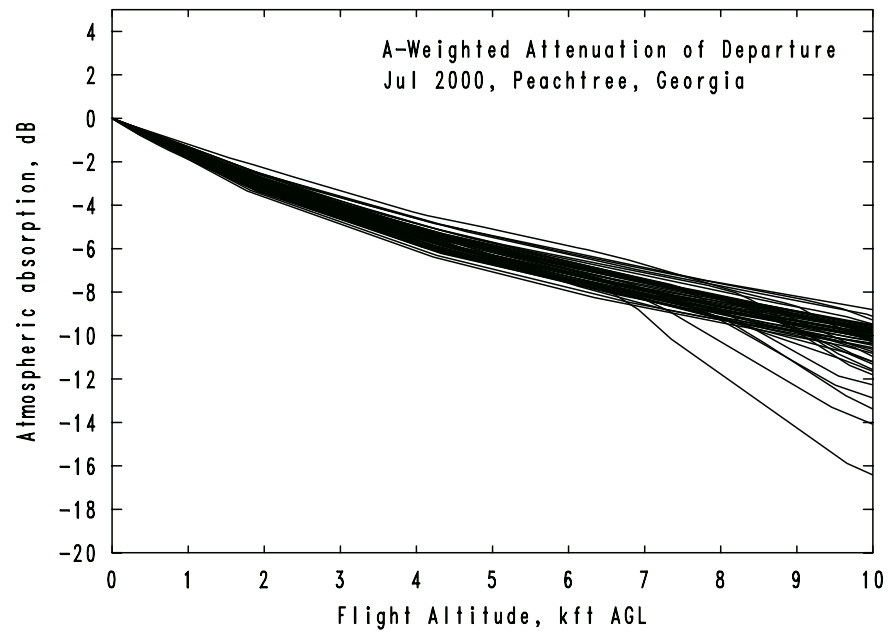
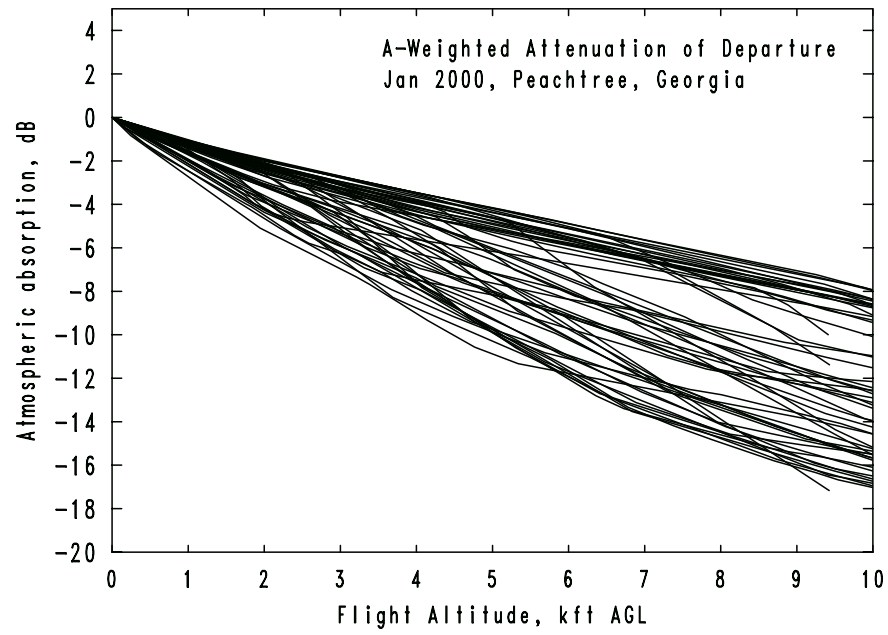


Figure 52. Attenuation of A-Weighted Level from 737, Peachtree Winter and Summer

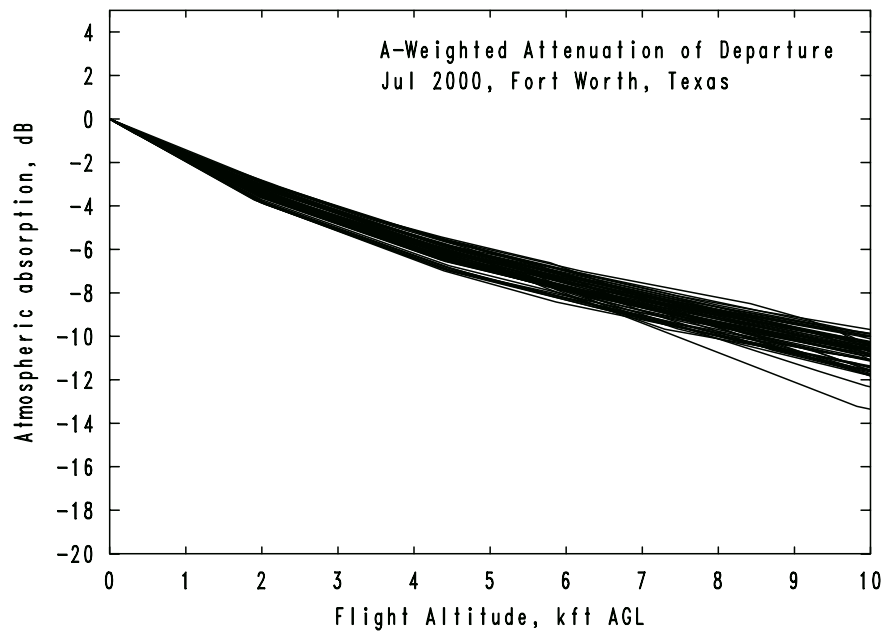
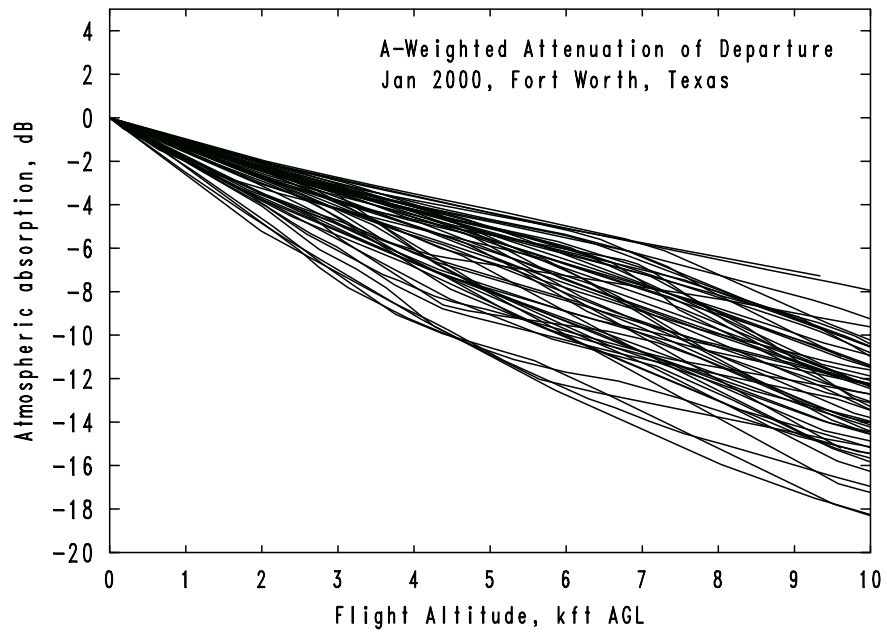


Figure 53. Attenuation of A-Weighted Level from 737, Fort Worth Winter and Summer

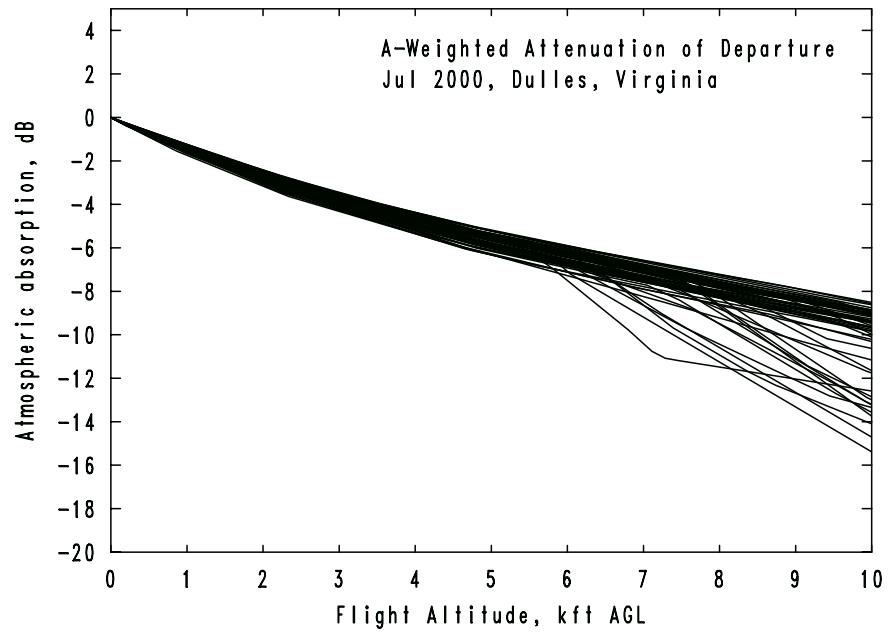
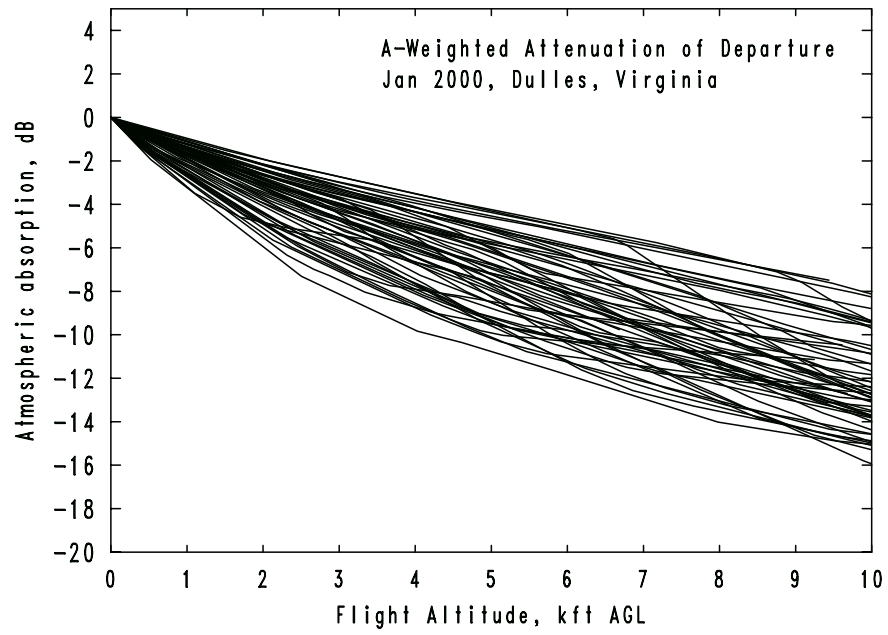


Figure 54. Attenuation of A-Weighted Level from 737, Dulles Winter and Summer

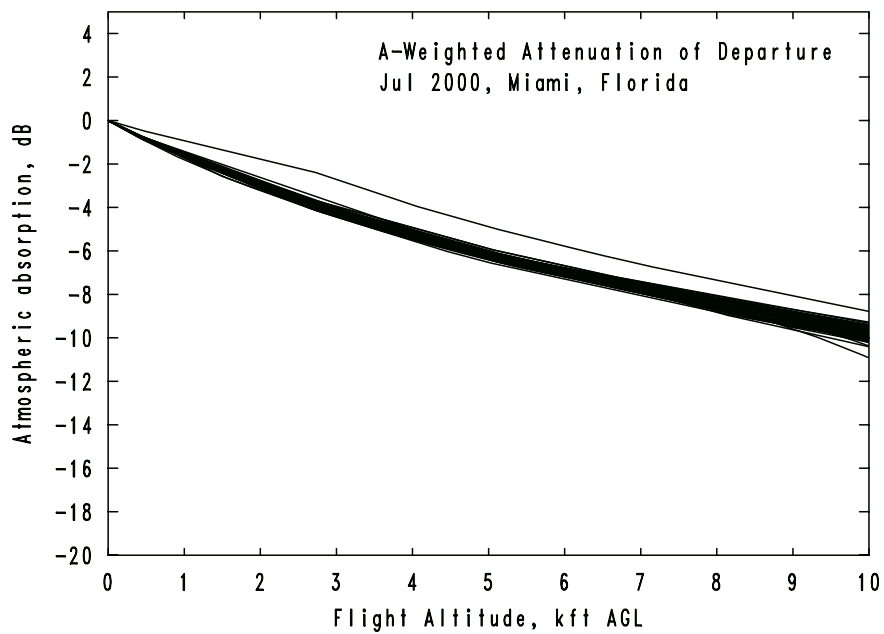
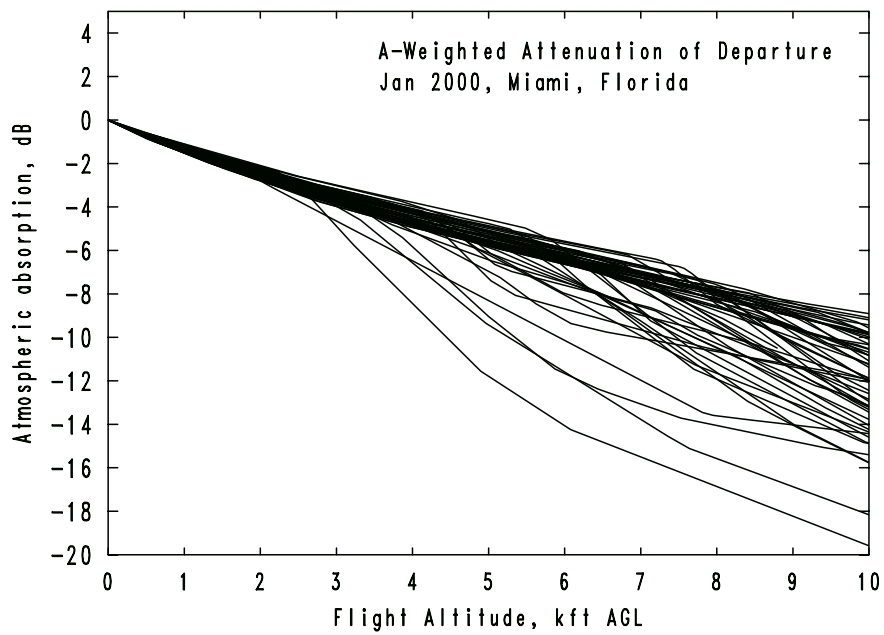
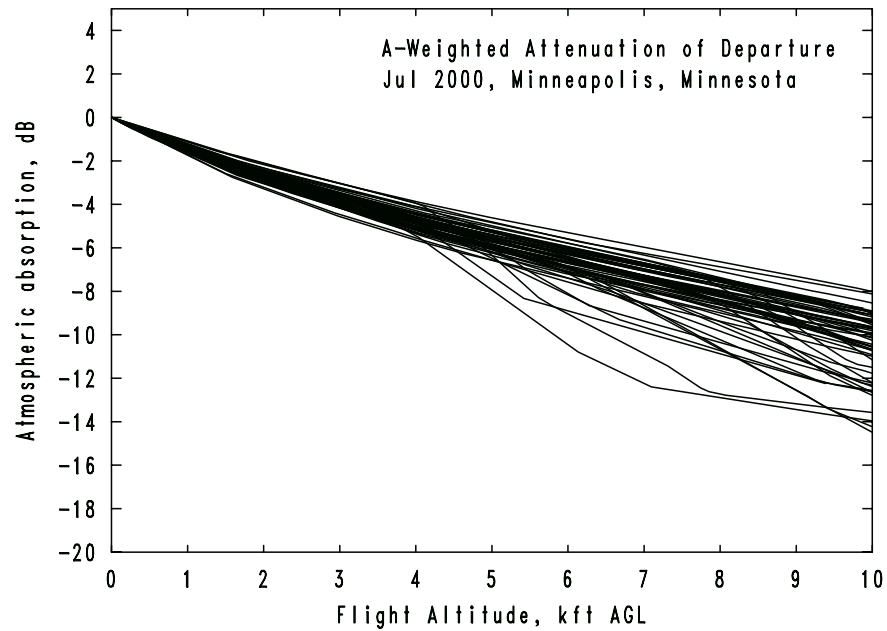
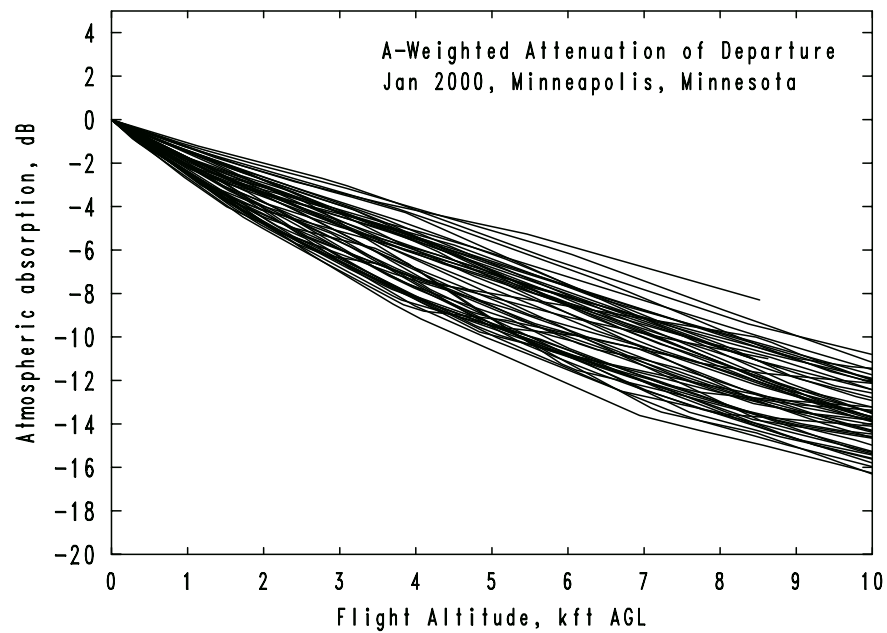
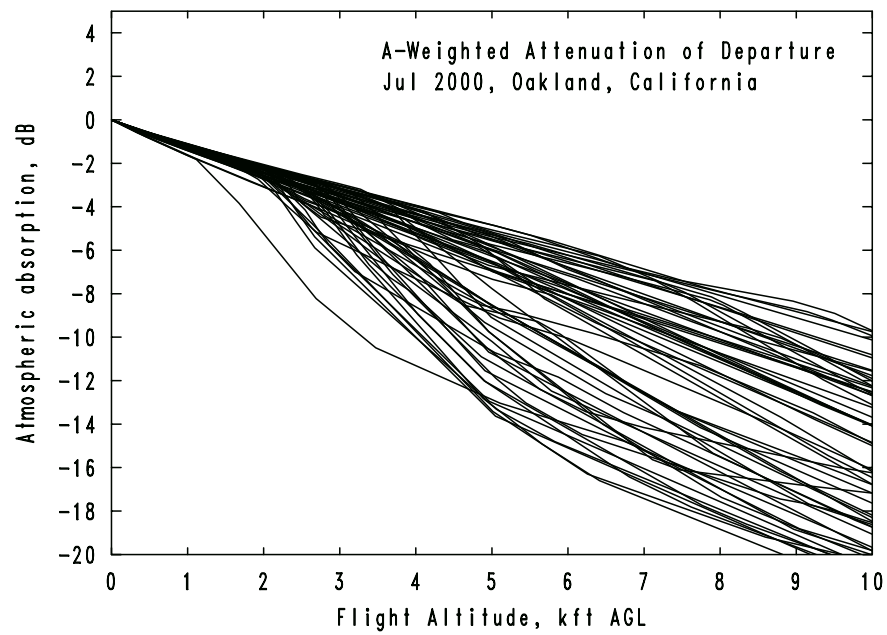
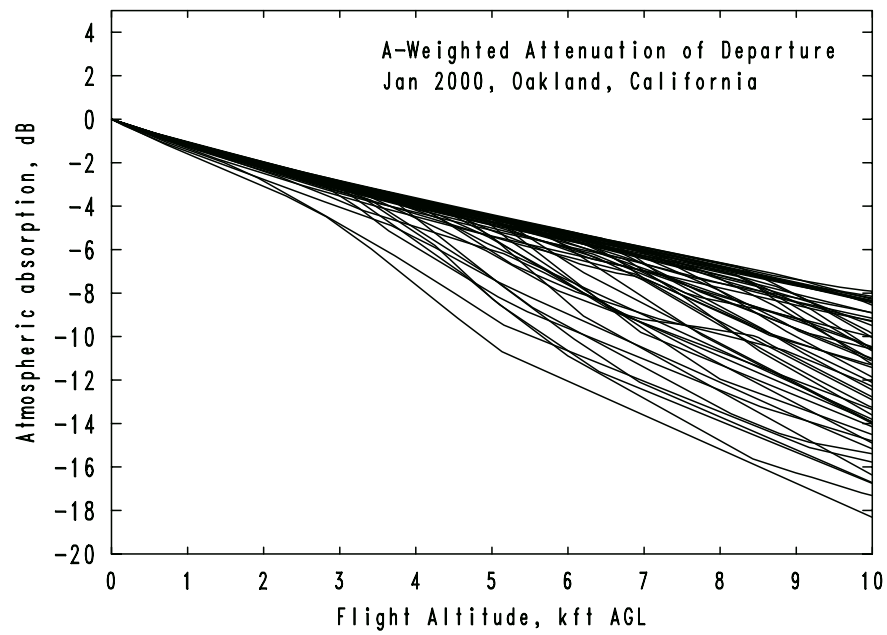


Figure 55. Attenuation of A-Weighted Level from 737, Miami Winter and Summer



**Figure 56. Attenuation of A-weighted level from 737, Minneapolis Winter and Summer**



**Figure 57. Attenuation of A-Weighted Level from 737, Oakland Winter and Summer**

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## 4.0 Conclusions

An analysis has been performed of a subset of noise model validation data collected around Denver International Airport in 1997. The subset consisted of straight-out departures from Runway 08. All flights were ones for which equipment type and takeoff weight were known, and for which power profiles had been prepared. Tracks and altitude profiles were taken directly from radar data. Surface and upper air weather were available for the test period. Emphasis was on flights which had generated good noise data on four or more monitoring sites.

Noise predictions using INM had fallen below the measured data. Review of noise at sequential monitors showed that measured noise was consistent relative to predictions. There was therefore a systematic shortcoming in the modeling; differences were not in general stochastic. To evaluate propagation effects, the noise simulation model NMSIM was employed. A three dimensional spectral source model (required by NMSIM) was prepared, based on INM's NPD curves and spectral classes. The source model was calibrated so as to replicate the SEL values in the NPD tables.

NMSIM calculations of SEL were found to be closer to measurements than INM calculations. INM 6 was found to be closer to measurements than INM 5. When run at standard atmospheric conditions, however, all of the models fell short of measurements. Stage 3 737 aircraft fell short more than hushkitted Stage 2 727 aircraft, and exhibited more variability. These differences were consistent with expectations from differences in spectral shape and the characteristics of molecular absorption.

NMSIM was run with actual time-of-flight atmospheric conditions for each flight. Air absorption was computed according to the current ANSI standard. Average predictions for 727s were within one dB of measurements. Average predictions for 737s were two to three dB below measurements. It is possible to speculate on the reasons for this offset, but no specific cause could be found.

INM noise predictions were always lower than the NMSIM simulation model predictions. Air absorption coefficients specified in SAE AIR 1845 are, in the important frequency range below 1 kHz, generally higher than those computed for the flight test conditions. This is part of the reason for some of INM's underprediction of noise.

Analysis of the Denver data showed that atmospheric absorption can be significant in the calculation of noise around airports. A general analysis of air absorption at several airports was undertaken. It was found that the nominal attenuation in SAE 1845 was generally within the range of actual absorption using local upper air profiles and ANSI standard air absorption. There is, however, a considerable variation from day to day. At altitudes of several thousand feet air absorption can represent variations of up to  $\pm 4$  dB about the average predicted sound level. In most places, it was found that variation in the winter was much larger than in the summer. Day to day and seasonal variability are sufficiently large that any model validation study over a limited period should account for actual conditions. It is also concluded that a proper statistical analysis should be performed to determine if there is any bias associated with the nominal attenuation commonly used.



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14. ABSTRACT An analysis has been performed of measured and predicted aircraft noise levels around Denver International Airport. A detailed examination was made of 90 straight-out departures that yielded good measurements on multiple monitors. Predictions were made with INM 5, INM 6 and the simulation model NMSIM. Predictions were consistently lower than measurements, less so for the simulation model than for the integrated models. Lateral directivity ("installation effect") patterns were seen which are consistent with other recent measurements. Atmospheric absorption was determined to be a significant factor in the underprediction. Calculations of atmospheric attenuation were made over a full year of upper air data at seven locations across the United States. It was found that temperature/humidity effects could cause variations of up to $\pm 4$ dB, depending on season, for the sites examined. It was concluded that local temperature and humidity should be accounted for in aircraft noise modeling.						
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